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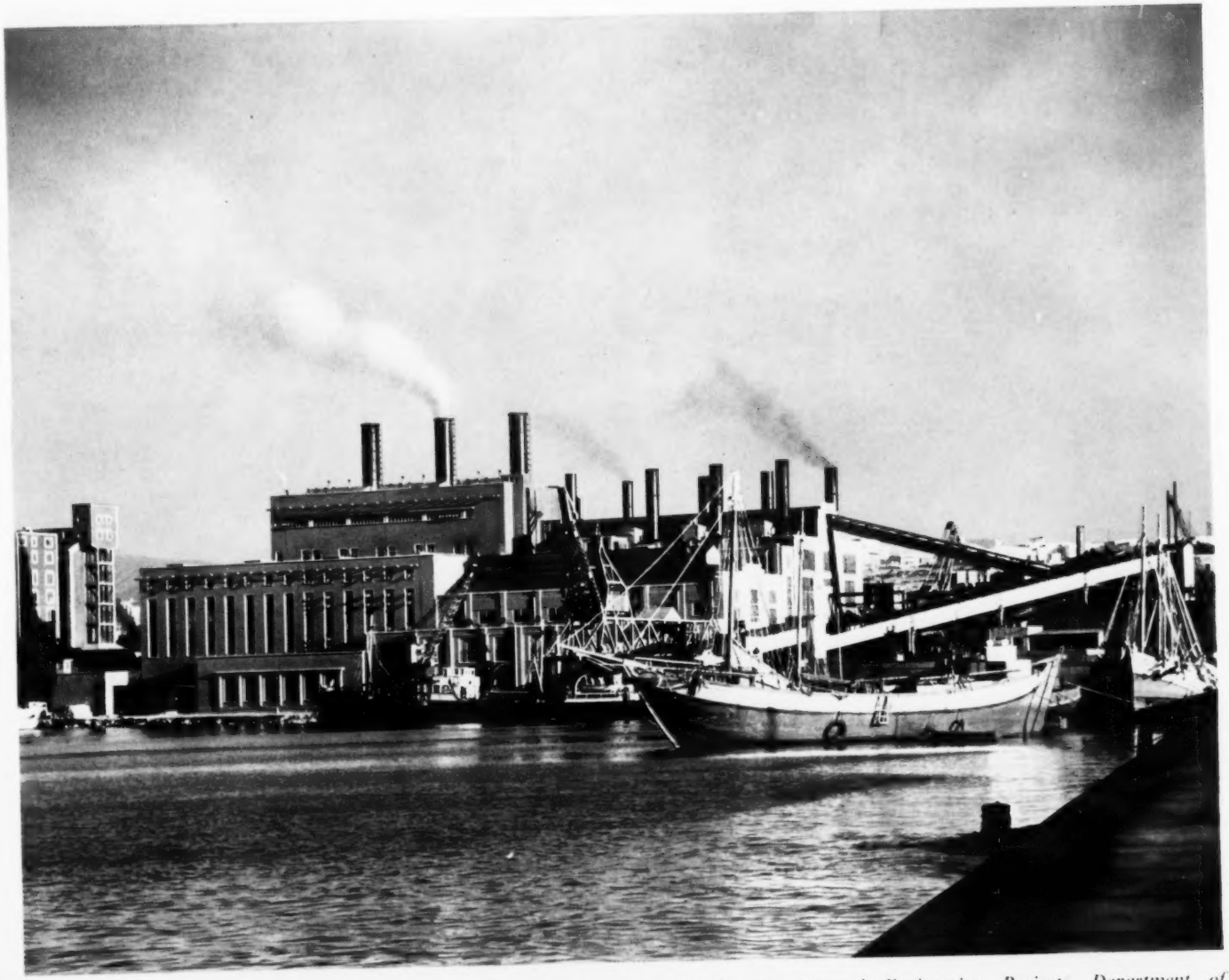


St. George's Bay Power Station, Athens, designed and engineered by the General Engineering Projects Department of The English Electric Company

Present Trends in Large Power Station Auxiliaries and their Electrical Equipment

By W. K. SIKORA, Dipl.Eng., A.M.I.E.E., General Engineering Projects Department.

In 1944 The English Electric Company decided to set up a committee of representatives from its Liverpool and Stafford Works to investigate the present and future requirements of power station auxiliary electrical systems and equipment. The committee, under the chairmanship of Mr. W. E. Streete, A.R.Ae.S., Assoc.I.E.E., of the Commercial Manager's Office, Stafford, found it convenient as its work progressed to add other representatives from the Company's London Branch, the General Engineering Projects Department and the Atomic Power Division. The purpose of this investigation has been to ensure that suitable machines and electrical equipment are made available to meet the needs of progressively larger boilers and turbines. The committee has issued several reports which have been circulated to certain overseas territories, and as a result of the interest shown, particularly in Australia, the following article has been prepared.

THE DEMAND FOR larger and larger generating units has been created by the trend towards large interconnected power supply systems, the economic advantages of which have become better understood. At present steam turbo-alternator units up to 550 MW are being built in the United Kingdom, and future 700 or 800 MW units are under consideration.

Progress in steam turbo-alternator design has been made possible chiefly by thermal and mechanical improvements enabling higher steam pressures and temperatures to be used in the turbine, resulting in rapid increases in rating and a better heat rate.

Similarly, the alternator cooling system particularly has undergone major changes, resulting in a considerable increase of rating within a given frame size and weight. The progress in turbo-alternator design has been matched by boiler manufacturers in producing high capacity steam generating units.

In the United States, development is well ahead with supercritical pressure cycles up to 5,000 p.s.i.g. and temperatures of 1,200°F. The general level of the steam conditions, however, is showing signs of stabilising around 2,300 p.s.i.g., 1,050/1,050°F single reheat. These advanced steam conditions obviously imply wide modifications to conventional auxiliaries systems, as considerably larger individual as well as total auxiliaries loads have to be accommodated. The tremendous changes in unit ratings and thermal characteristics over the last few decades are illustrated in Figs. 1 and 2.

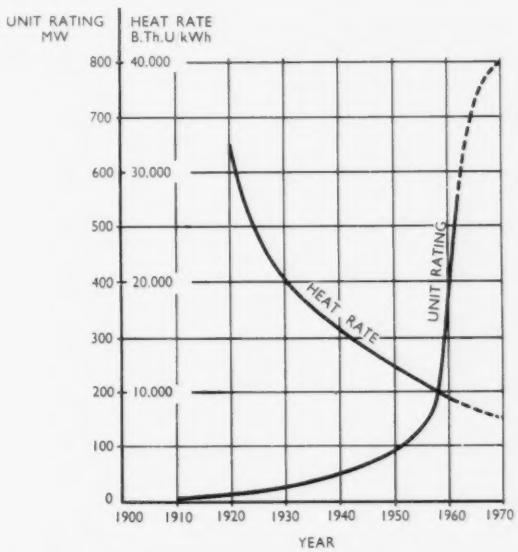


Fig. 1.—Progress in unit ratings and heat rate

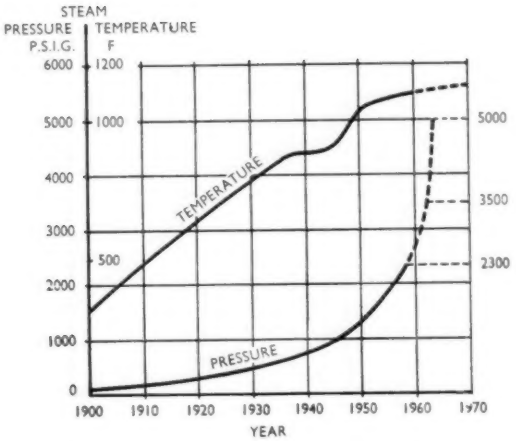


Fig. 2.—Progress in steam conditions

The advent of nuclear power stations, although presenting numerous problems regarding auxiliaries for reactors, has actually caused reversion to lower steam conditions and ratings of turbo-alternators associated with this plant, at least for the time being. There is little doubt however that progress will result in more advanced steam conditions, with consequent increases in the ratings of reactor and generating units.

The purpose of this article is to re-examine the established practice in auxiliaries systems in the light of present-day developments. To limit the scope of the article, only power stations with generating units of 200 MW and above have been considered, with some references to lower ratings.

REQUIREMENTS FOR AUXILIARIES

The auxiliaries for a power station should provide an economic degree of reliability combined with high efficiency as well as ease of operation and maintenance. The degree of reliability should be considered in relation to the financial risk of forced outage or damage to the plant. Such evaluation can be carried out accurately only if adequate statistical information on plant operation is available. Even then the figures obtained should be considered in the light of experience in power station operation.

An analysis of auxiliaries load shows that this is concentrated in a few auxiliaries which take about 70% of the power: these include boiler feed pumps, boiler fans and circulating water pumps. The remaining auxiliaries consist of a large number of smaller drives and consequently present no problems. It is therefore obvious that the large auxiliaries are establishing the general pattern to be adopted. In this section a brief survey is made of present-day practice and future trends regarding these auxiliaries.

Boiler Feed Pumps

The capacity of boiler feed pumps is proportional to the steam consumption of the main plant and to the total head required. In practice a margin is necessary to make allowance for make-up water, soot blowing, boiler blow-down, and increased boiler pressure to the safety valve blow-out setting. A further margin is usually included to allow for working at reduced electrical supply frequency and for reduced efficiency of the pump within its lifetime. These margins together constitute about 15% of the pump motor rating. During normal operating conditions, and particularly when the unit operates at part load, the excess quantity and head have to be dissipated by one means or another.

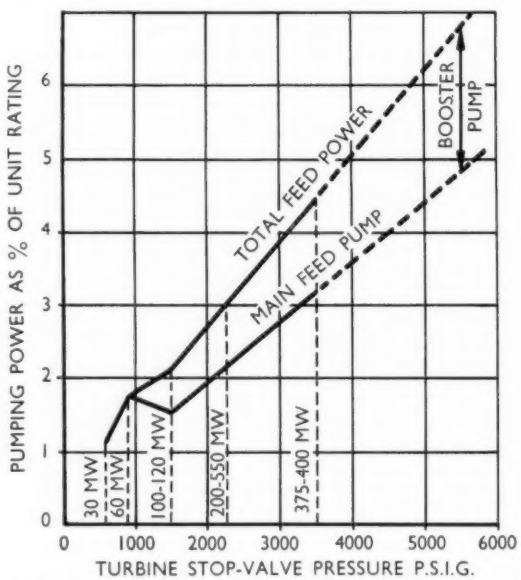


Fig. 3.—Approximate boiler feed pumping power requirements

The feed pump constitutes an appreciable portion of the auxiliaries load, particularly for the larger units operating at advanced steam conditions, as can be seen from Fig. 3. Furthermore, at pressures above 1,000 p.s.i.g. the single-feed-pump arrangement is becoming less economical due to increased cost of feed heaters which have to be designed for full pump discharge pressure. It is therefore a general practice to provide a split-feed-pump arrangement for units of 100 MW and above operating at advanced steam conditions.

The increasing rating of feed pumps associated with larger units presents two major problems. The first is the selection of the most economical and reliable drive, and the other is associated with the high losses due to dissipation of head when the pump is operating below design duty. Both problems have a bearing on the design of the auxiliaries supply system if motor drive is selected.

For unit ratings up to 200 MW, drives for main feed pumps by squirrel cage motors have been generally accepted, the standby pump being either separate-turbine or electrically driven. For machines rated 275 MW and above, a number of drives are open for consideration, namely:—

(*a*) Main pump driven from main generator shaft through variable speed coupling, and electrically driven standby pumps, the booster pump being either electrically or shaft driven.

(*b*) Separate-turbine driven main pump and electrically driven standby and booster pumps.

(*c*) All pumps electrically driven by squirrel cage motors.

(*d*) Main pumps electrically driven by slipring motors with speed control. The booster and standby pumps driven by squirrel cage motors.

In the first two arrangements the burden on the auxiliaries supply is greatly eased, as provision is necessary only for 50% duty standby feed pumps and the booster pumps. An economical comparison between these two arrangements shows that generator shaft drive is cheaper than separate turbine drive. The principal disadvantage of the generator shaft drive is the reliance on large variable-speed fluid couplings, of which operating experience at present is limited. Another point is the complication at the generator end to accommodate the feed pump and exciter.

Arrangement (*c*) with the squirrel cage motor drive for main feed pumps (Fig. 4) has the attraction of greater reliability and less maintenance. However, due to the increased losses in head dissipation in the feed regulator, and associated erosion of the valve, the general trend is towards some form of economical variable-speed drive. The large slipring motors recently available for 3,000 or 3,600 r.p.m. operation will no doubt influence this trend considerably. The analysis of pump characteristics for a 275 MW unit shows that the range of speed control required is approximately 8% for full load operation, with a maximum of 13·5% from no

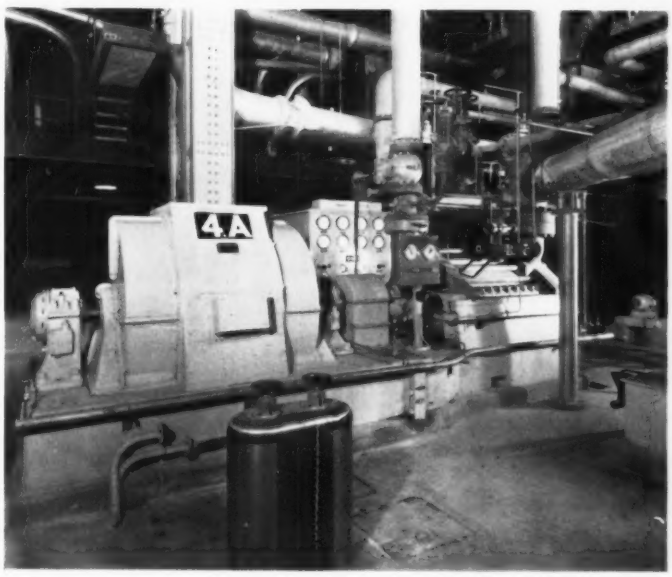


Fig. 4.—Boiler feed pump driven by 2,070 h.p. 2,950 r.p.m. 3·3 kV squirrel cage motor with closed air circuit and water cooling

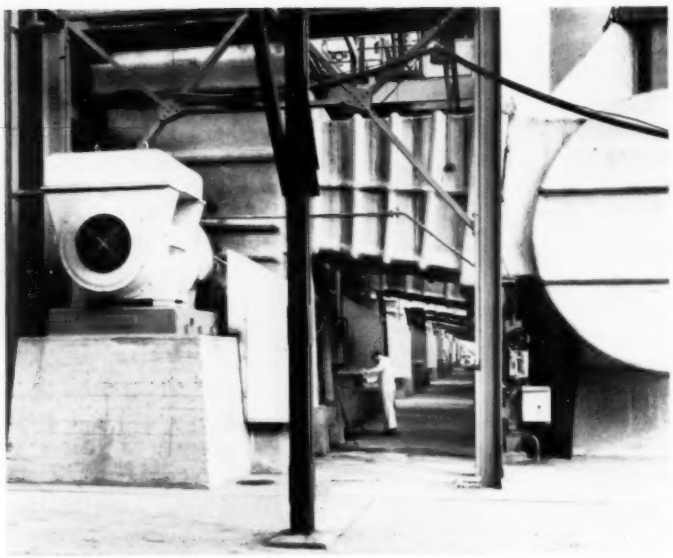


Fig. 5.—Induced draught fan driven by 388 h.p. 740 r.p.m. 3·3 kV squirrel cage weatherproof motor with closed-air-circuit air cooling

load to full load. This small range of control can easily be obtained by available equipment.

The availability of feed supply to the boilers is extremely critical, as its failure may result in considerable and costly damage to the boiler plant. It is therefore an established practice to provide standby feed pumps arranged for automatic starting. For the smaller generating units one standby pump, either electrically or steam driven, may be used for a number of units ; however, for the larger units this is not practicable and individual standby is provided. This usually consists of two 50% duty pumps with their motors connected to the station supply. Squirrel cage motor drive for the standby pumps is the most favoured because of its simplicity and high degree of availability as well as its quick starting characteristic.

Boiler Fans

The volume of air delivered by a centrifugal fan is proportional to its speed, and the driving power to the cube of the speed. On the other hand, the control of air flow of a constant-speed fan necessitates throttling by inlet vanes or dampers, both of which are inherently wasteful. Furthermore, the induced draught fans are subjected to erosion by the hot flue gases, and the rate of erosion increases approximately with the third power of the speed. It is therefore logical to control the fan output by a variable-speed drive. Such drives are however more expensive and their reliability compares less favourably with that of a robust directly coupled squirrel cage motor (Fig. 5).

Due to its inherent reliability the two-speed squirrel cage motor is a favoured arrangement for the larger units, with inlet vane air flow control. Often the lower speed is chosen to provide sufficient air flow for boiler operation at the normal full load condition, without allowance

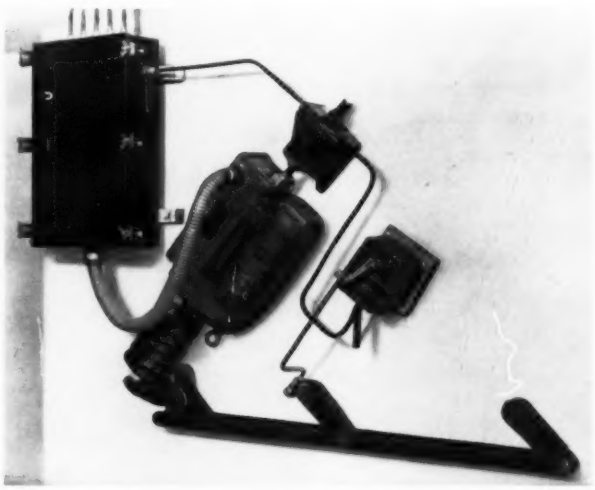


Fig. 6.—'English Electric' boiler damper actuator Type 291 and position transmitter at Keadby power station

for operational margins and assuming a clean boiler with fuel at normal calorific value. The higher speed is called for only when the boiler is operating at conditions outside the normal design duty.

In assessing the rating of fans, allowance is made for fouling of boiler and flue ducts, as well as increased volume handled by induced draught fans with rise of flue gases temperature. In addition, a margin is allowed for reduction in the efficiency of the fan during its lifetime. All these margins combined increase the installed fan power above normal operating requirements by about 20-30% for forced draught fans and 30-60% for induced draught fans. It is questionable whether computation of all abnormal conditions occurring simultaneously is justified, and greater care in assessing the ratings of fans and drives would no doubt contribute to increased efficiency of the station.

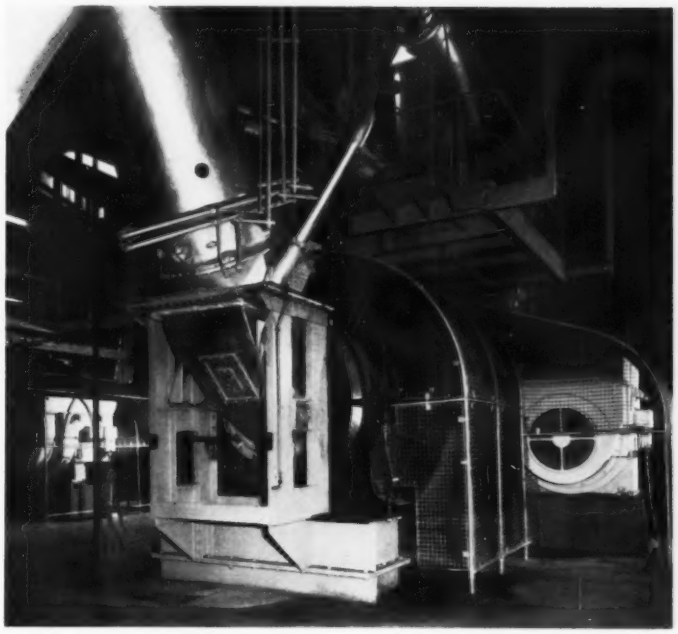


Fig. 7.—Pulverised fuel mill driven by 515 h.p. 590 r.p.m. 3·3 kV high-torque squirrel cage motor with closed-air-circuit air cooling

The arrangement of fans varies considerably for different boiler designs. For the smaller units up to 60 MW, single 100% duty fans are common. For larger units, two for 50% duty are preferable on account of fan design considerations and increased operating flexibility, and for very large units with multi-furnace boilers the number of fans will increase accordingly.

It is necessary to establish roughly the total power requirements for fans in the early stage of power station design, and these can be taken as about 0·5% of unit rating for the forced draught fans and 0·8% for the induced draught fans.

Pulverising Mills

The number of pulverising mills varies with the boiler design and type of coal, but four or six mills per boiler is a popular arrangement for small and medium size units. For very large units of 550 MW and 800 MW an increase in the number and size of pulverisers is necessary. For the smaller stations a centralised pulverising system is sometimes used, but for the larger stations the unit arrangement has a number of advantages on account of lower capital cost, simpler layout and operation.

As a first approximation it can be taken that the total power required by these mills is about 0·5% of unit rating, this being without any allowance for standby capacity.

Circulating Water Pumps

The circulating water arrangement may be of the cooling tower type, river type, or a mixed system. Generally, the river system requires less power on account of the smaller quantities of water needed due to a lower intake water temperature ; also the effective head in the river system is reduced if syphonic action in the water discharge is provided.

The centralised station system with one or two main discharge headers is the practice usually adopted, but for the larger generating stations the

circulating water pumps are associated with the units. Standby pumps are sometimes provided, with their motors connected to the station supply. The trend is however to dispense with standby pumps and instead to increase the capacity of the unit pumps in such a way that on failure of one pump, the remaining pumps can cope with the total water requirements of all units. Sometimes this increased capacity is calculated to allow for normal vacuum to be maintained at station full load only in winter time. This means that reduced efficiency is accepted should failure of one pump occur in summer with the station operating at full load.

The power requirements for circulating water vary considerably with the site conditions and the system adopted, but close figures are available at an early stage of power station design. A provisional assessment of 0·3-0·6% of unit output can be taken for a station using river-water cooling and 0·5-1·0% for a cooling tower station. The higher figures refer to the smaller units while the lower figures are associated with large units operating at advanced steam conditions.

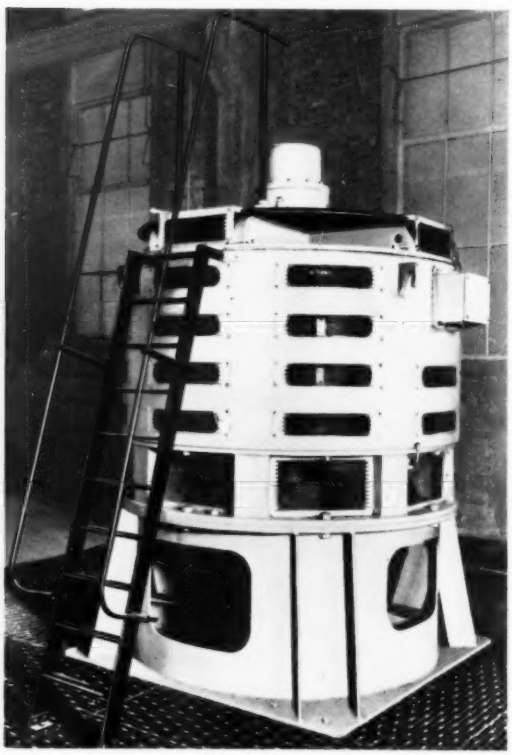


Fig. 8.—Vertical spindle squirrel cage motor, 1,180 h.p. 425 r.p.m. 3 kV, driving circulating water pump

Condensate Extraction

The condensate extraction pumps do not present any special problems of either a mechanical or electrical nature. A high degree of reliability of extraction is however necessary to prevent dangerous conditions which may arise if the water level in the condenser rises above a safe limit. For this reason it is the usual practice to provide two 100% duty pumps for each unit. The standby pump, however, is started manually on receiving the alarm that the main pump has failed.

For generating units with a reheat cycle it may be necessary to dump the steam in the condenser during emergency shut-down to avoid damage to superheaters, and this must be provided for with supercritical steam pressure turbines. The availability of the standby extraction pump under these conditions is of the utmost importance, and automatic starting from an independent supply is necessary.

Other Auxiliaries

The auxiliaries which have been described constitute the largest single items associated with the unit. The remaining numerous unit auxiliaries require comparatively small driving power individually, and consequently do not present particular problems in power station design. Their importance and reliability cannot be neglected however, as failure of some of them may affect the continuity of operation of the boiler plant, generating unit or the step-up transformer.

Two groups of auxiliaries require more specific attention in a coal fired station. These are coal and ash handling plant drives which contribute appreciably to the auxiliaries power demand. The arrangement for this plant is dependent on the type of fuel, site conditions and method of firing. While it is not possible to quote general figures, 0·3-0·5% of unit rating can be taken for a preliminary assessment of the combined load for both plants, the lower figure being applicable to the larger stations.

The excitation is generally provided by shaft-driven exciters although in some instances separately driven exciters have been provided for large units. With increasing turbo-alternator ratings the d.c. exciter becomes large, and serious consideration has been given to shaft-driven a.c. exciters with rectifying equipment. For a cross compound unit a standby separately driven exciter is necessary for starting-up purposes. When the unit is up to speed the excitation is changed over to the shaft-driven exciter on each generator.

REQUIREMENTS FOR AUXILIARIES SUPPLY

The power requirements for steam power plant auxiliaries are determined by a number of factors, the chief of which are : unit rating, heat cycle, circulating water arrangement, type and handling of fuel, and ash disposal. These factors are established at an early stage of design as they form the fundamental parameters of the station. A preliminary assessment of the power required can therefore be made at an early date, thus enabling a decision to be reached on the auxiliaries system to be adopted.

The auxiliaries can be grouped broadly as (1) unit auxiliaries, i.e. those associated directly with the generating unit, and (2) station auxiliaries, i.e. general station services which include also provision for starting and emergency or standby supply. Table I shows typical auxiliaries loads as a percentage of unit rating. The figures are average and indicate the total capacity of running auxiliaries, that is excluding standbys.

For the reasons mentioned in the previous section it is necessary to include a margin in ratings of power station auxiliaries, and consequently most auxiliary motors run at less than full load when the station is operating at full load under normal conditions. A load factor is thus obtained which reduces the actual maximum demand to approximately 70-80% of the running installed power for the auxiliaries.

Unit Supply

Over the last decade the idea of unit power generation has been widely accepted and its advantages appear to be even more attractive for the larger units being installed at present and planned for the future. The unit auxiliaries system asso-

TABLE I

TYPICAL AUXILIARIES LOADS AS A PERCENTAGE OF UNIT RATING

Unit		Percentage of Unit MW Rating							
Rating MW	Steam Condition	Boiler feed	Circul. water	Boiler auxil.	Turbo-alt. auxil.	Coal and ash	Station services	Total Unit	Total Station
30	600 p.s.i.g. 850 F	1·2	1·0–1·5	4	0·5	0·5	0·5	6·7–7·2	1·0
60	900 p.s.i.g. 900 F	1·8	0·6–1·0	3·8	0·3	0·5	0·4	6·5–6·9	0·9
100	1,500 p.s.i.g. 1,050 F ..	2·2	0·5–0·7	3·5	0·3	0·4	0·3	6·5–6·7	0·7
120	1,500 p.s.i.g. 1,050/1,000 F	2·2	0·5–0·7	3·5	0·3	0·4	0·3	6·5–6·7	0·7
200	2,350 p.s.i.g. 1,050/1,000 F	3	0·3–0·5	3·3	0·2	0·4	0·25	6·8–7·0	0·65
275	2,300 p.s.i.g. 1,050/1,000 F	3	0·3–0·5	3·3	0·2	0·4	0·2	6·8–7·0	0·6
300	2,300 p.s.i.g. 1,050/1,000 F	3	0·3–0·5	3·2	0·2	0·4	0·2	6·7–6·9	0·6
550	2,300 p.s.i.g. 1,050/1,050 F	3	0·3–0·5	3·2	0·2	0·3	0·2	6·7–6·9	0·5
800	2,300 p.s.i.g. 1,050/1,050 F	3	0·3–0·5	3·2	0·2	0·3	0·1	6·7–6·9	0·4
375	3,500 p.s.i.g. 1,100/1,050/1,050 F	4·4	0·2–0·4	3·2	0·2	0·3	0·2	8·0–8·2	0·5

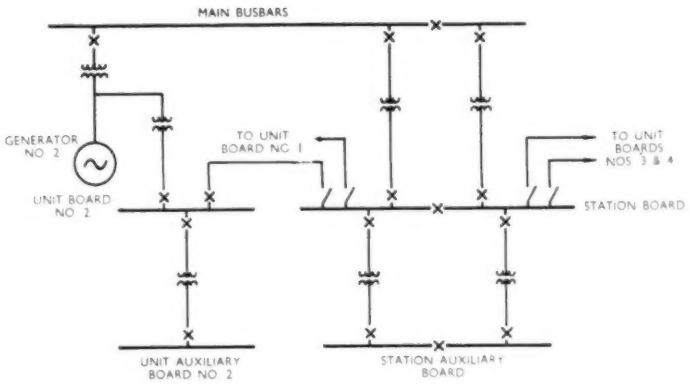


Fig. 9.—Basic arrangement of unit auxiliaries system

ciated with unit generation is based on two independent sources of supply, one derived from the generating unit and supplying the unit auxiliaries, and the other from the station busbars and supplying station services as well as providing standby for the unit auxiliaries. A typical arrangement is shown in Fig. 9.

The unit supply derived through a unit transformer connected directly to the generator has proved to be reliable and economical. It is true to say however that unit transformer supply is susceptible to disturbances during severe faults on the main system, but the system disturbances are somewhat cushioned by the impedance of the generator transformer. Furthermore, with the application of high-speed protection, and the ability of the modern motor to recover its speed after a momentary voltage drop, the unit transformer has held its position.

The rating of the unit transformer is usually based on the total connected capacity of running unit auxiliaries, i.e. excluding the standby drives. Accordingly the transformer is operating at about 75% full load throughout most of its life. The additional capacity is justified however on account of the extremely high reliability required of the auxiliaries system. Moreover, the spare capacity is available to maintain full output during abnormal conditions. Fig. 10 shows typical relative ratings of a unit transformer and a generator unit operating at sub-critical pressures.

Up to about 300 MW unit rating, operating at sub-critical pressures, the straight unit scheme as shown in Fig. 9 can be applied, with some qualifications. Above 300 MW the ratings of the unit and station transformers are inconveniently high, particularly with electrically driven boiler feed pumps. One solution to this problem is the division of unit auxiliaries into two or more sections, each section being fed either through two half-size unit transformers or one double-secondary transformer. The basic arrangement is shown in Fig. 11. This arrangement involves two or more operations to change over from station to unit supply and *vice versa*, depending on the number of sections introduced. This complicates slightly the procedure when starting-up and shutting-down the units, but is, in the author's opinion, of minor significance.

For the cross-compound generating units the

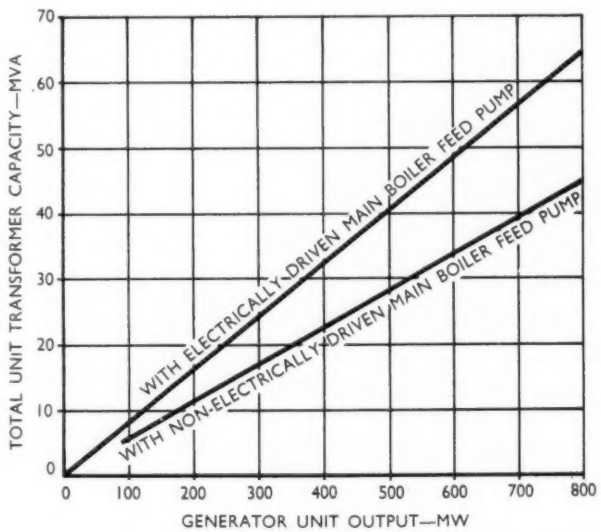


Fig. 10.—Typical unit transformer capacities for units operating at sub-critical pressures

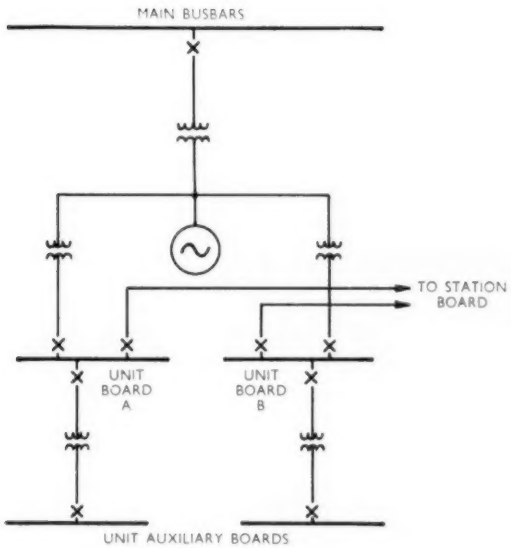


Fig. 11.—Basic arrangement for sectionalised unit auxiliaries

sectionalisation can be carried out by connecting one (or more) unit transformers to the terminals of each of the two generators, as indicated in Fig. 12. Such an arrangement introduces a small out-of-balance, depending on the condition of the auxiliaries load, but this should have no operational significance.

For large generating units operating at high steam pressures the method of driving the boiler feed pumps is the main consideration. As can be seen from Table I, the feed power demand for a steam pressure of 2,300 p.s.i.g. is about 50% of the total auxiliaries load, and even higher for 3,500 p.s.i.g. If therefore non-electric drive for the main feed pump is selected the capacity required for the unit transformer is correspondingly reduced, as illustrated in Fig. 10.

Station Supply

For unit type stations a supply independent of the individual units is necessary and the station supply must be available when all units are shut down. As large stations usually operate in interconnected systems the simplest method is to derive this supply from the main busbars through step-down transformers. For stations which are intended for operation in isolated systems an additional starting supply is necessary in the form of a self-contained house set.

The station supply is therefore obtained by either one or two station transformers feeding a station switchboard. Two 100% duty transformers are usually provided for stations with more than two units. The extra cost of the second transformer and associated switchgear may however be justified for a single or two unit station if an extremely high degree of availability is required.

The station supply should have sufficient capacity to meet the following load conditions simultaneously :—

(*a*) All running auxiliaries for station services at full station load.

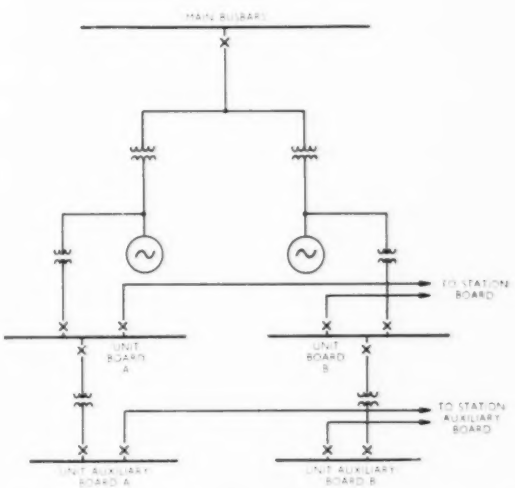


Fig. 12.—Basic arrangement for cross-compound unit auxiliaries

(*b*) The running auxiliaries of one unit operating at full load.

(*c*) The auxiliaries load for starting one or more units simultaneously.

For stations with comparatively small units the rating of the station transformer is not very critical and a commonly used rating in many new stations is 1·5 times that of the unit transformer. For large units however, every effort is made to reduce the

standby capacity. Typical ratios of station to unit transformer ratings are given in Table II. These are based on the foregoing considerations and for various numbers of units in the station.

TABLE II

TYPICAL LOAD REQUIREMENTS FOR STATION TRANSFORMERS

Number of units	Number of station transformers	Simultaneous loads (defined in text)	Station/ Unit* load ratio
1	1	(a)+(b)	1·0
2	1	(a)+(b)+(c)	1·5
2	2	(b)	1·0
More than 2	2	(b)+(c)	1·3

* Unit load including boiler feed pumping power.

It should be noted that for single unit stations the unit transformer rating must be increased to provide also for station services in the event of failure of the station supply. In such stations therefore the unit and station transformers are of the same rating.

The load for station services depends on the ultimate number of units, type of fuel and associated handling plant. Typical figures for coal fired stations are given in Table I. About half these values is required for oil fired stations.

Selection of Voltage

For generating units up to about 100 MW a two-voltage system using 3·3 kV and 415 V has been generally adopted in Great Britain. For larger units however, with increased auxiliaries demand, the fault level and current rating are limiting factors in the economical design and manufacture of 3·3 kV switchgear. Furthermore, the voltage regulation and copper losses of the system become embarrassingly high.

For these larger units it is therefore desirable to raise the distribution voltage, and in Britain 6·6 kV is being used for 120 MW and 200 MW units operating at 2,300 p.s.i.g., and 11 kV for larger units. However, with increased unit ratings, difficulties are encountered on the low voltage switchgear of the auxiliaries system due to fault level, which becomes the limiting factor. With a three-voltage system many of the difficulties can be obviated while the simplicity of a straight unit system can be retained for still larger unit ratings, and in certain instances some easement can be obtained by the use of 550 V instead of the standard voltage of about 400 more generally employed.

The voltage drop on starting the auxiliaries does not normally present special problems except in the case of the boiler feed pumps. The feed pump motor is generally much larger than any other auxiliary and although starting current is restricted, it is of sufficient magnitude to cause a considerable dip in the supply voltage when the motor is switched on.

In order to ensure satisfactory starting, feed pump motors are designed to have sufficient accelerating torque with voltage down to 80% of the normal value.

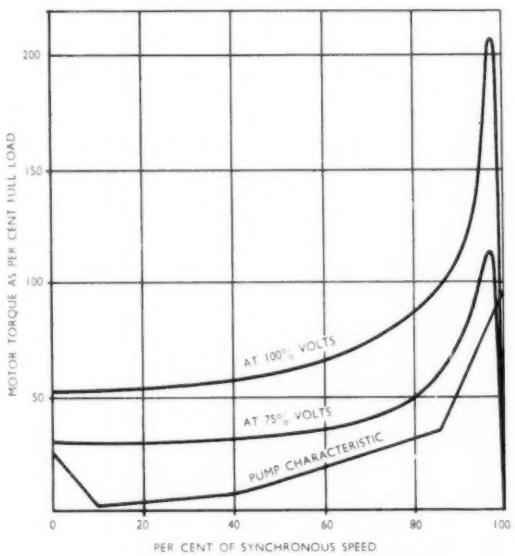


Fig. 13.—Typical torque-speed characteristics of a 6,200 h.p. 3,000 r.p.m. feed pump motor

All essential auxiliaries motors for British power stations are now designed to operate for 10 minutes at 75% of normal voltage. A typical characteristic of motor torque in relation to speed at 100% and 75% voltage is shown in Fig. 13.

It is apparent that some voltage adjustment is useful at the transformers and it is the usual practice to provide off-circuit tappings of $\pm 2{\cdot}5$ and $\pm 5\%$ on unit and station transformers. When the main system voltage fluctuation is wide the station transformers are provided with on-load tap-changers. The ratio of the transformers at neutral tap position should be selected to provide near nominal system voltage at normal load. This is obtained closely enough if the ratio is based on 75% load at 0·8 power factor.

Fault Level

The voltage selected for an auxiliaries system is closely associated with the fault level, and both have to be considered in order to determine the most economical arrangement, the next higher standard voltage being adopted when the rating limit of available switchgear of a given voltage is reached.

It is desirable to have means of paralleling the station transformers (where two are provided) for change-over purposes, and the paralleled condition therefore establishes the maximum fault level on the station board. On the unit board the highest fault level which need be considered occurs when one station transformer and one unit transformer are paralleled. Provision for this condition appears to be satisfactory, although interlocks are necessary to prevent paralleling both station transformers with a unit transformer. On this basis it may be justifiable in some instances to provide unit switchgear for a lower fault level than that on the station board.

The breaking capacity of unit switchgear could be further reduced if it would not be required to deal with the fault level during the brief period of paralleling the unit and station transformers. Reactors inserted between the paralleled supplies may be an economical proposition if the fault level during the transition period exceeds the rating of the switchgear by an amount of up to 20-30%.

The induction motors contribute a fault current of short duration due to the effect of residual magnetism. This current approaches the motor starting current at full voltage and decays within a few cycles. This contribution for a 200 MW unit with a total motor load on the unit board of 14,000 h.p. (13 MVA) amounts to approximately $13 \times 5 = 65$ MVA. It is therefore advisable to take this into consideration when calculating the fault level of the auxiliaries system.

Earthing

Opinions on the type of earthing for auxiliaries systems vary considerably, but the main differences are centred on the question of whether an earth fault should cause immediate tripping of the affected circuit or should initiate an alarm. It is argued that in the latter case the affected circuit can remain in service until alternative arrangements for the supply can be made at a convenient time.

Solid or resistance earthing is therefore provided when immediate tripping is accepted. With solid earthing the system voltage surges are lowest, while with resistance earthing, earth fault current can be reduced to a comparatively small value. Voltage-transformer earthing with an alarm reduces the unexpected outages, but equipment so earthed may be subjected to severe voltage surges, with possibility of insulation weakening.

The present trend appears to be the choice between solid earthing and voltage-transformer earthing, depending on the operating mode required. The extra cost of resistance earthing and the additional accommodation necessary are not really justified, particularly for transformer ratings and voltage levels in large stations.

For the main earth connection present practice appears to favour one common station earthing system. To this system are connected all neutrals, structures, tanks, switchgear, motor enclosures and cable sheaths. Thus the whole station forms an equipotential area within which the voltage gradients are reduced to minimum under all fault conditions.

The earth connections are usually made of bare copper strips which are fixed in trenches or along the cable supports, and solidly connected to the main earthing ring. For connections laid direct in the ground some bituminous or plastic serving is recommended as protection against corrosion. The cross-section of the copper strip can be chosen on the basis of a temperature rise of 400°C after 3 seconds, and this gives a current rating of approximately 80,000 amp/sq in. The minimum section

however should not be less than 1 in. × $\frac{1}{8}$ in. on account of mechanical damage.

The lead sheath and armour of cables are solidly bonded to the body of the terminating equipment which in turn is bonded to the main station earth. Small distribution and terminal boxes and small motors up to about 100 h.p. can be earthed through the armour and sheath of the cable. In the case of single core cables it is necessary to bond the sheaths together and this usually done by plumbing a width of lead sheathing round the individual sheaths of the three-phase group. For a long run of a three-phase group, intermediate bonding is provided for about every 50 yards of run to keep the sheath voltage rise within reasonable limits under short-circuit conditions.

Auxiliaries Control

The trend towards increased centralisation of controls, and to a certain degree of automation, is evident in modern power plant. This is due to the small operating margins inherent in large units operating at advanced steam conditions.

Boiler automatic control maintains the balance between fuel, air and water supply for a set output. In addition a sequence and inter-trip control is provided to prevent incorrect operation of auxiliaries, or to shut down the fuel supply in the event of dangerous conditions arising. The decrease in boiler temperature would cause severe stresses in the turbine, while sudden decrease in pressure might result in water carry-over with consequent damage to turbine blading. Automatic turbine unloading is therefore provided, and alarms are initiated if abnormal thermal expansion takes place. The standby auxiliaries on which the safety of the plant depends are arranged for automatic start-up, initiated electrically on failure of the main auxiliary or by an abnormal condition of pressure, water level or temperature.

The control and instrumentation of boiler and turbo-alternator units are centralised to allow for overall supervision by one operator who can thus make adjustments, if these are necessary, without delay. It has become the practice to centralise all controls of auxiliaries associated with starting, running and stopping of the entire unit in a separate ' plant ' or ' unit ' control room. For convenience and economy one room is provided for each pair of units and is located at or near the turbine floor level between these two units. In some cases provision for synchronising the generating units has also been included. This however complicates somewhat the arrangement and does not appear to be really necessary as synchronisation as well as loading of the unit can conveniently be carried out from the electrical control room.

The electrical control room thus accommodates equipment for unit load control and load despatch. The control of the main supply circuits for the auxiliaries is also carried out from this room. With this arrangement the dividing line of responsibility is clearly defined between the unit and electrical control room operators. For stations with one or two units and simple load distribution it is practicable to combine both control rooms into one, with consequent reduction in cost and the number of operators. The future trend may well be towards the single control room for large stations—a trend which is already reflected in nuclear stations.

Automatic switching of selected standby and emergency auxiliaries is necessary to prevent dangerous conditions arising on failure of running auxiliaries or on emergency shut-down of the plant. Sometimes automatic change-over of the entire unit auxiliaries to station supply is advocated. This however introduces a major problem. Due to the magnitude of inrush current in an induction motor at the initial time of circuit reclosure, it is necessary to introduce a time interval of a few seconds duration between the loss and reinstatement of supply. Tests carried out on motors indicate that shorter time intervals result in high inrush current which may exceed appreciably the motor stalling current. As a consequence the motor winding is subjected to severe mechanical stresses with resulting progressive damage and possible ultimate failure. On the other hand with delayed reclosing the motors run down practically to standstill and the kVA demand on restarting all auxiliaries simultaneously causes severe voltage-drops in the system. The supply system can, of course, be designed to cope with this condition, but at the cost of higher capacity and reduced overall efficiency.

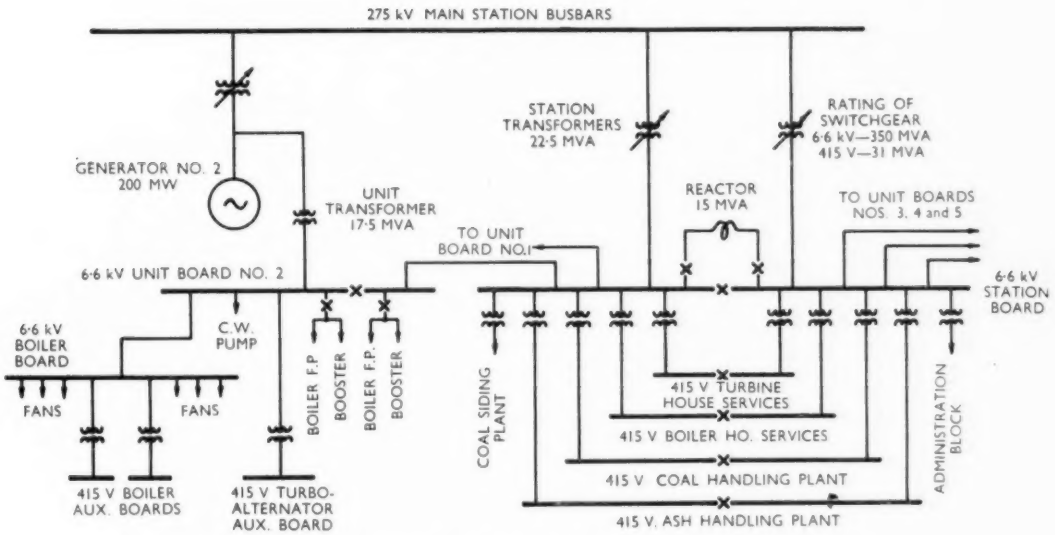


Fig. 14.—*Basic auxiliaries system for High Marnham* 5 × 200 *MW station*

Failure of the main supply is usually the result of a major fault, which should be investigated, and in these circumstances automatic change-over does not serve any useful purpose. Generally, the additional expenditure and complications involved in providing complete automatic change-over would not be justified for stations with large units.

Typical Arrangements of Auxiliaries Systems

The arrangement of the auxiliaries system is a matter of detailed consideration throughout the design of the station. Consequently, the type of drive, supply, distribution system, and layout have to be co-ordinated to obtain the best and most economic solution. All these factors must in turn be related to the conditions associated with a particular station, and it is therefore possible to refer only to a basic auxiliaries system.

Fig. 14 shows the basic auxiliaries system for a large station consisting of five 200 MW generating units. This station is now under construction in the United Kingdom and is designed to operate at 2,300 p.s.i.g., 1,050°F/1,000°F single reheat. The main and booster feed pumps are driven by squirrel cage motors rated 6,150 h.p. and 1,575 h.p. respectively.

As can be seen from the diagram, voltages of 6·6 kV and 415 V have been adopted. To allow for paralleling both station transformers without exceeding the 350 MVA fault level capacity of the switchgear, a reactor is inserted between the two sections of the station switchboard.

A typical arrangement of auxiliaries for a station consisting of four units of 275 MW is shown in Fig. 15. Electrically driven main boiler feed and booster pumps are assumed, having 50% duty capacity. For this station a three-voltage system appears to be convenient, and the maximum fault level at 11 kV is approximately 500 MVA when the two station transformers are in parallel and at the lowest tap-change position. All boiler pumps are connected to a double-busbar section of the unit board to allow convenient selection of any one pump as standby to be fed from the station supply.

A similar arrangement could be used for a station of 300 MW units, but above that size either 750 MVA breaking capacity switchgear is necessary or the auxiliaries have to be sectionalised. It should be noted that with mechanically driven boiler feed pumps the unit auxiliaries load would be considerably reduced, but the station supply

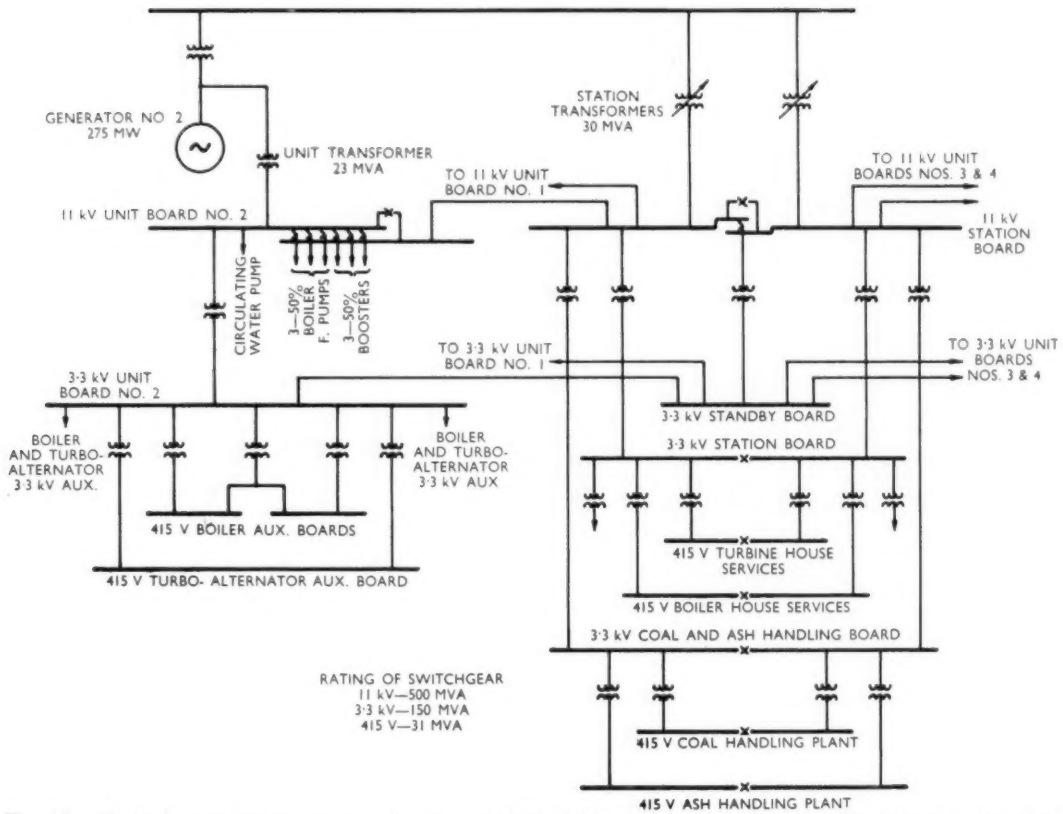


Fig. 15.—Typical auxiliaries system for a 4 × 275 MW station with electrically driven boiler feed pumps

capacity is not altered as this has to provide power for the standby feed pumps.

A preliminary arrangement for a station consisting of two 800 MW cross-compound type units operating at 2,300 p.s.i.g. has been investigated. One of the possible arrangements is shown in Fig. 16. It has been assumed that the main boiler feed pumps are not electrically driven. The capacity of each station transformer would allow replacing the load of only one unit transformer and at the same time supplying the standby feed pumps at full load. For a station consisting of 550 MW cross-compound units a similar arrangement could be used, and the fault level on the 11 kV switchgear would be reduced to 500 MVA.

In all the foregoing arrangements the main feed pump if electrically driven forms part of the main unit auxiliaries system. It may be of some advantage to separate the supply to these pumps and feed them at generator voltage, through reactors to reduce the fault level, as shown in Fig. 17. Motors of the size required could be manufactured for operation at 16·5 kV, which is the generating voltage for very large units.

NUCLEAR POWER STATIONS

Considerable progress has been made in nuclear power plant development over the last few years. The gas cooled reactor has been adopted in the United Kingdom for commercial application, while in the United States concentrated efforts are being made to develop the boiling water type reactor. In the gas cooled reactors the heat

produced by the core containing fissionable uranium is removed by circulating CO_2. This heat is then passed through the heat exchangers, where steam is produced at the pressure and temperature required for the turbo-alternator plant. Fig. 18 shows the flow diagram for a typical 250 MW gas cooled reactor unit.

The steam conditions obtained at present are low, this being due to limitations imposed principally by the available material for canning the fuel. Further research and development is however being carried out and it appears likely that within the next few years very much higher steam conditions will be reached. Due to improvements in construction, further increases in output per reactor are within sight.

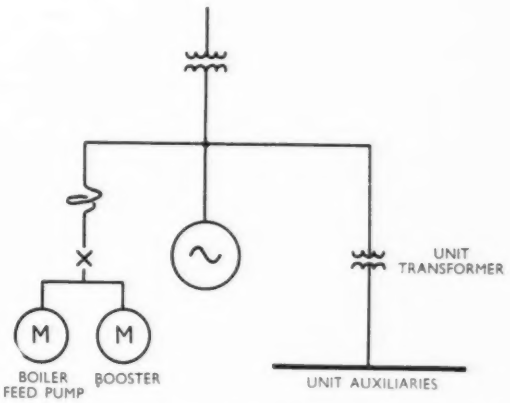


Fig. 17.—Arrangement for the supply of boiler feed pump motors direct from generator terminals

Auxiliaries

The problems associated with auxiliaries for nuclear stations differ in many ways from those for conventional steam plant. Firstly, a large amount of power is required for circulating the coolant through the reactor, and fine control of circulation is necessary within a wide range. Secondly, the emergency requirements necessitated by an uncontrolled shut-down of the plant are extremely stringent. This is primarily due to the ability of the reactor to generate delayed heat during a period after shut-down. A certain

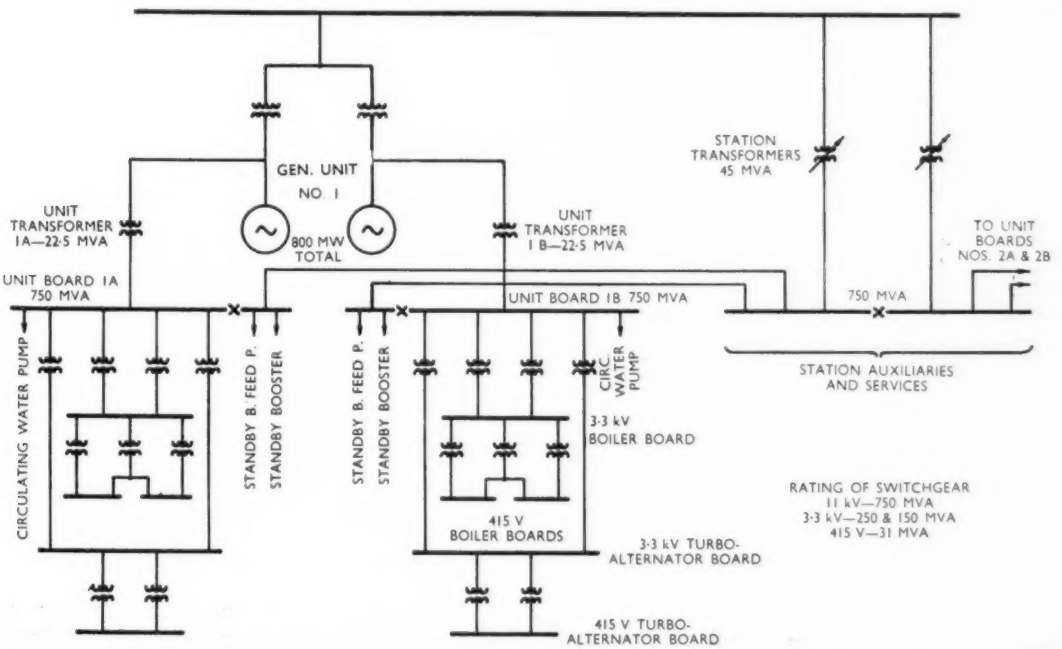


Fig. 16.—Typical auxiliaries system for a 2 × 800 MW station with non-electrically driven main boiler feed pump

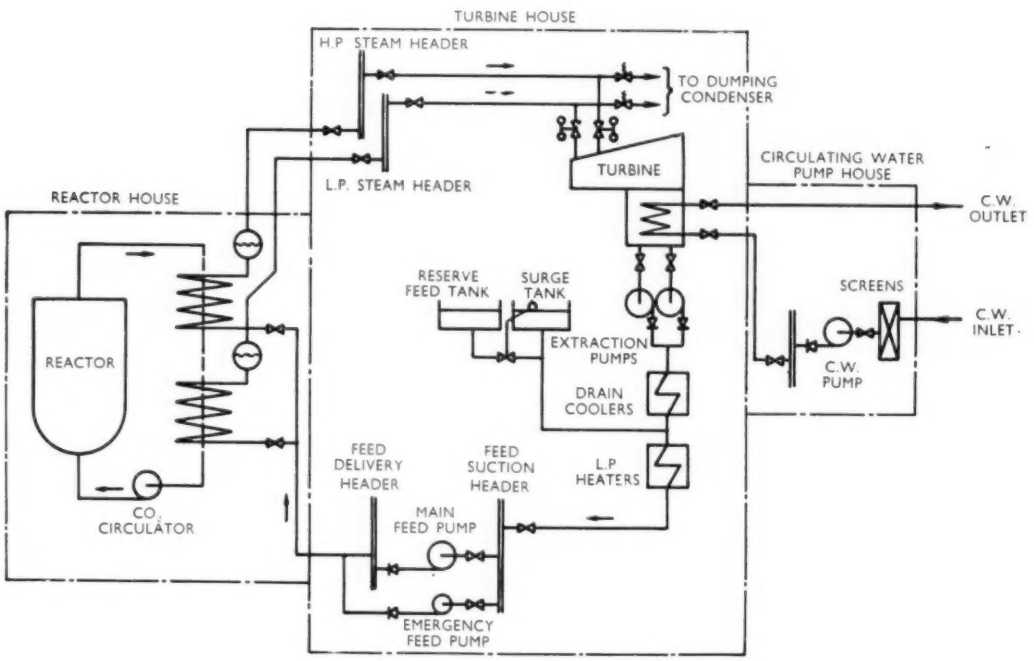


Fig. 18.—Simplified flow diagram for a 250 MW gas cooled reactor unit

amount of coolant must therefore remain in circulation to remove this heat. In addition, shield cooling and gas sealing as well as the supply to safety circuits must be maintained in service. The feed system must also remain operative, although only a small fraction of its normal flow is necessary to prevent excessive temperatures in the heat exchangers. It will be appreciated that all these essential auxiliaries must be available in the condition of emergency when the unit and station supplies may also be lost.

A further characteristic of nuclear reactors that has some bearing on auxiliary system design is that after a rapid shut-down the reactor cannot achieve full power again until many hours later, due to the build-up of ' poisoned ' elements which are normally kept at a suitably low level.

Detailed consideration of auxiliaries for nuclear plant is outside the scope of this article, and only main characteristics are briefly discussed in the foregoing paragraphs. The basic arrangement of an auxiliaries system for a typical 500 MW station consisting of two reactor units is shown in Fig. 19.

As can be seen from this diagram the unit system is applied to the reactor and three associated turbo-alternators. As for conventional stations the station supply is derived from the main busbars by two 100% duty transformers. This supply acts as standby to the normal unit supply as well as providing the necessary power for starting-up and for station services. A characteristic feature of the arrangement shown is the duplication of feeders to all switchboards associated with the reactor, as well as to all services. The emergency supply for the reactor essential auxiliaries is based on d.c. from batteries for the initial period of shut-down and is supplemented by diesel-generator sets which are started automatically on operation of the master trip relay.

The auxiliaries power demand for nuclear plant is high compared with that of a conventional high-pressure steam station. A typical figure for a two-reactor-unit station of 500 MW output is

about 13% of power sent out ; of this almost 70% is absorbed by the gas circulators.

Thus the method of driving the gas circulators has a considerable influence on the design of the auxiliaries system. At Hinkley Point power station it was found that the best choice, taking into account overall economics and using current engineering practice, was an electric induction motor drive supplied from an 11 kV system separate from the other auxiliaries system and fed by steam driven variable-frequency turbo-generators.

The remainder of the normal running auxiliaries system of 50 cycles offered no problems, as no unusual quantities of power were involved, so that this is supplied from a conventional 3·3 kV and 415 V arrangement.

Present developments indicate that the gas circulators in future stations may be supplied from the main auxiliaries system. Under these conditions it may be necessary and even economic to use a three-voltage system to solve the electrical problems involved. The actual system for any particular case will depend largely on the number and size of the gas circulators ; these are tending to become larger and fewer in number per reactor.

Gas Circulators

The drives for gas circulators require most careful consideration. This is due to the large power involved, combined with a wide range of mass flow control necessary. In addition they must be able to provide a small amount of circula-

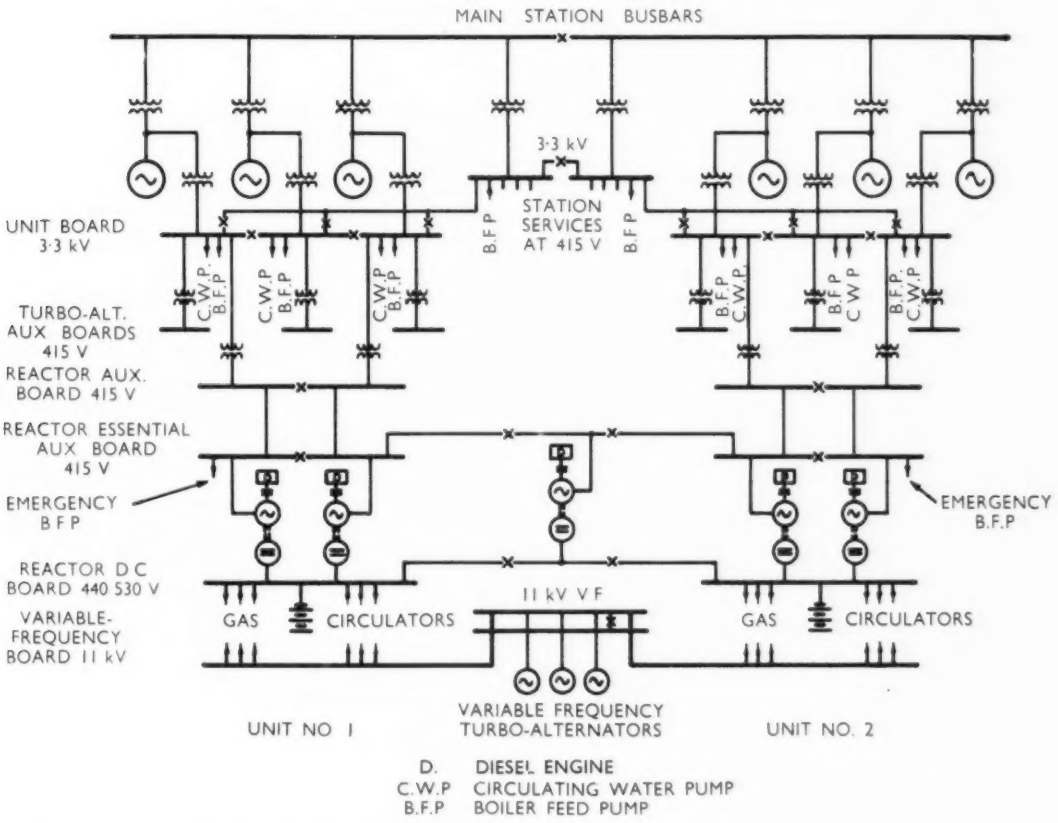


Fig. 19.—Basic auxiliaries system for the first 500 MW nuclear power station, at Hinkley Point

tion under extreme emergency conditions, when the normal power supplies are lost.

From an economical and operational point of view, electric drive is probably the best choice. Effort is therefore concentrated on producing the most reliable and advantageous means of mass flow control in association with motor drives. A number of arrangements are possible, of which the following have been and are being considered:—

(1) Variable frequency generator supplying squirrel cage motors.
(2) Variable speed slipring motors with slip loss recovery or plain rotor resistor.
(3) Constant speed squirrel cage motors with the following possible means of obtaining mass flow control :
   (*a*) Gas bypass.
   (*b*) Circulator blade angle variation.
   (*c*) Hydraulic coupling.

The choice between these arrangements is influenced mainly by the capitalised running costs which are affected by the unit rating and load factor.

The auxiliaries supply arrangement is considerably affected by this choice ; for instance a variable frequency scheme obviously requires a separate system, and for slipring and squirrel cage motors in (2) and (3) the required high capacity of unit and station supplies creates problems of fault level and current rating.

Water Moderated Reactors

The problems of auxiliaries for water moderated reactors are very similar to those for gas cooled reactors. The total auxiliaries load demand is about 9% of the output for a 200 MW reactor unit. This is due to the smaller power requirements of the main coolant pumps compared with gas circulators. Additional problems with this type of reactor are created due to radio-active steam in the cycle. These problems are, however, mainly of a constructional nature.

AVAILABLE ELECTRICAL EQUIPMENT AND FUTURE TRENDS

The electrical equipment for power station auxiliaries incorporates special features, and The English Electric Company has developed switchgear, control gear, transformers, motors and actuators for this application.

High Voltage Switchgear

The trend towards air-break switchgear for auxiliaries systems started two decades ago. This type of gear is well established today and is likely to remain for a long time. It is well suited for power station application on account of the high degree of safety combined with suitable performance characteristics. The fire hazard is practically non-existent due to absence of oil, and fire fighting equipment can therefore be dispensed with. Maintenance requirements compare very favourably with those of the oil-type gear, and a high degree of availability is obtained. Furthermore, absence of current chopping reduces the over-voltages in the system and minimises outages due to insulation failures.

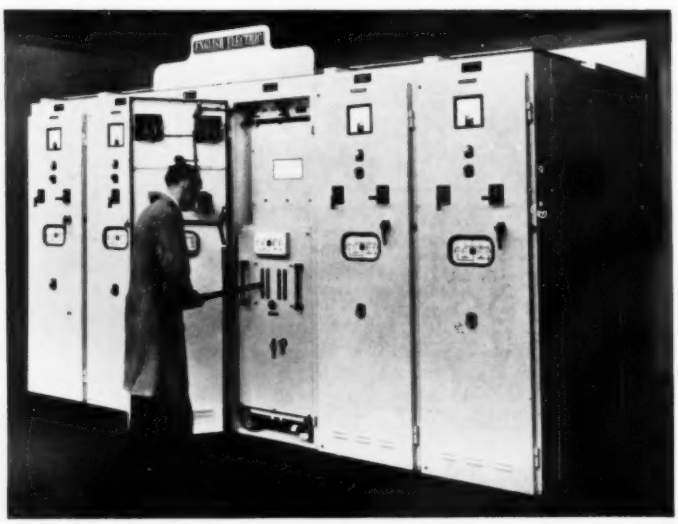


Fig. 20.—*Class* '*E*' 3·3 *kV* 150 *MVA switchboard, showing manual emergency operation of one circuit-breaker*

For the higher voltages of 3·3 kV, 6·6 kV and 11 kV, the Class 'E' range of air-break switchgear is available. This has been developed specifically to meet the requirements of modern power stations, and embodies all necessary interlocks to ensure completely safe operation. The truck mounted circuit-breakers are of the shunt-trip medium-speed type with a total opening time of approximately 5 cycles, which is satisfactory for protection of the equipment and for maintenance of system stability under fault conditions. Solenoid operation from the battery is usually provided, being most suitable for power station application.

The stationary portion is of sheet steel construction and incorporates single or duplicate busbars within the same standard dimensions, cable terminations, instrument transformers, and panels for mounting a limited number of instruments and relays. On-load busbar selection can be provided.

The range of air-break switchgear available or under development is given in Table III, and a typical switchboard is shown in Fig. 20.

Low Voltage Switchgear

For low voltage auxiliaries air-break switchgear is most suitable, for similar reasons to those given for the high voltage gear. Generally, for the main feeders and interconnectors, circuit-breakers are provided, while for outgoing circuits a combination of switch and high rupturing capacity fuse is satisfactory. Motor circuits incorporate in addition contactors with thermal motor protection. The 'Superform' distribution equipment developed by The English Electric Company incorporates all these features together with safety interlocks and ease of maintenance (Figs. 21 and 22).

The present practice is generally to limit the rating of 415 V motors to about 150 h.p. For the larger stations however the tendency is to increase this limit on account of the reduced cost of switchgear and motors, and probably a limit of about 200-250 h.p. would be more economical. Special consideration has to be given to motors in remote locations.

An increase of voltage to 550 V would no doubt ease many problems associated with current ratings and fault level, while involving no extra cost for the motors and switchgear. At the same time reduction in cable cost and copper losses would be quite significant.

The available ratings of the OB22-24 air circuit-breakers which are built into the 'Superform'

TABLE III

RANGE OF AIR-BREAK AIR-INSULATED SWITCHGEAR AVAILABLE

Type	Voltage kV	Current up to : amperes	Fault Rating MVA	Busbars SB—single DB—double
OB22	Up to 0·66	800	25 at 415 V	SB
OB23	Up to 0·66	1,600	31 at 415 V	SB
OB24*	Up to 0·66	3,000	31 at 415 V	SB
OB33L	3·3	2,000	150	SB
Class E3	3·3	2,000	150	SB or DB
Class E4/E5 ..	3·3	2,000	250	SB or DB
Class E5	6·6	2,000	250/350	SB or DB
Class E6	6·6	3,000	350	SB or DB
Class E7	11	2,000	500	SB or DB
(Projected)	11	2,000	750	SB or DB

* Under development.

Fig. 21.—Part of a station auxiliary switchboard of 'Superform' construction, comprising OB23 air circuit-breakers, fuse-switch units, instruments and meters

equipment are shown on Table III. The fuse-switches are available up to 750 A for on-load isolation, and above that, for off-load isolation, the ratings extend to 1,200 A for the fuses and 2,000 A for the switches. For motor circuits, contactors can be incorporated in the switchboard in combination with the fuse-switch units. The fuses are of the high rupturing capacity cartridge type and are suitable for use on systems having a fault level of 35 MVA at 415 V.

Solenoid operation is usually provided on all main feeder and interconnector circuit-breakers to allow for remote operation from the control room. The other feeders can be manually operated. Two distinct types of contactors are available—the electrically held-in and the latched-in types. The former type if a.c. operated is sensitive to supply voltage dips, and consequently d.c. operation from the station battery is generally preferred although with the disadvantage of the additional drain on the battery which may be quite high for a large station. The latched-in type has neither of these disadvantages, but is larger and requires more maintenance due to more complicated closing mechanism. For motors larger than 150 h.p. it is preferable to provide circuit-breakers instead of contactors.

It has become a frequent practice to centralise the low voltage switchgear together with the motor controls in complete switchboards which are located at convenient points within the power station. With this arrangement means of isolation, or at least of locking out the circuit at the motor, are desirable for safety. Another approach is centralisation of distribution with fuse protection and isolation, with the contactors located at the motors. In this case the switchboards incorporate outgoing fuse-switch combinations while the contactors are built into self-contained starters complete with incoming isolators. In either case the contactors are controlled from the remote control panels in addition to local control.

Fig. 22.—Compartment of switchboard accommodating 'Superform' fuse-switch and contactor

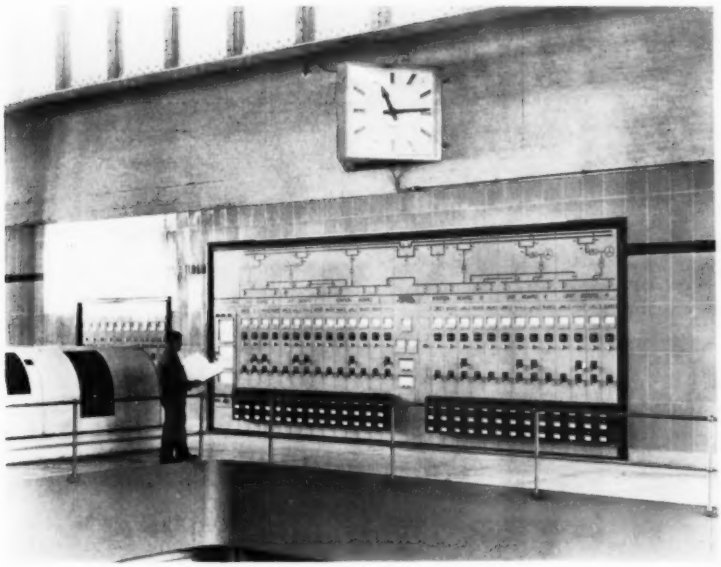


Fig. 23.
Power station auxiliaries control board

Control Gear

Auxiliaries control is centralised in appropriate panels or desks in accordance with functional requirements. Switching control is however also provided at the switchboards for maintenance purposes. Mimic diagrams are very helpful on control panels, with instruments and controls built into the diagram. This arrangement however should be used with discretion, particularly on plant control panels, as otherwise dislocation of instruments reduces the ability of the operator to follow the operation of the plant. Indicating lights and visual alarms arranged for 'dark' operation under normal conditions are preferable to avoid a constant multitude of lights, which is distracting. The English Electric Company manufactures various types of control boards and desks, built on the 'unitised' principle which allows for extensions or modifications to be easily carried out.

Transformers

Transformers for power station application are of standard design and of the oil insulated type. Natural circulation cooling is preferable for unit transformers due to absence of cooling fans and pumps and thus increased reliability. For station transformers of the larger ratings, above 15-20 MVA, mixed natural and forced cooling or water cooling is justified on account of lower cost and low load factor, but against these lower costs must be set the additional cost of providing the auxiliary

Fig. 24.—*Wall mounted pattern control panel*

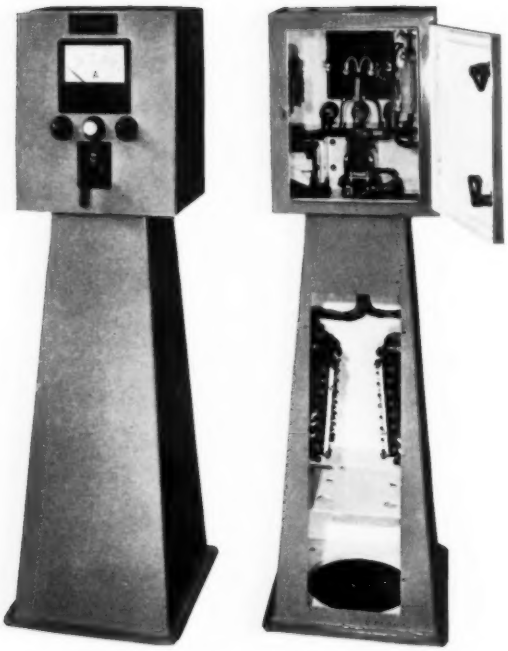


Fig. 25.—*Front and rear views of floor mounted pedestal type control box*

supply, cables and control gear, and of course the capitalised cost of the power used. In addition, in the case of the water cooled alternatives, there is the added cost of providing the water connection, means of circulating the water, and either the volume of water or means of cooling the water.

The relation of the cost of various types of cooling to that of natural cooling is indicated in Table IV. The values are approximate only, and applicable to voltages up to say 132 kV. At higher voltages the differences would be reduced due to the larger part of the total cost being represented by the basic transformer. In respect to the OFW cooling the factors allow only for 100% cooling without standby.

Water cooling has the attraction of reduced space requirements but unless dictated by other considerations the use of water should be avoided so as to preclude the possibility, however remote, of water getting into the oil, with consequent damaging effect on the transformer insulation.

The ratio between copper and iron losses is of

TABLE IV

APPROXIMATE COST RELATIONSHIP OF TRANSFORMER COOLING METHODS

MVA	O.N.	O.N./O.F.B.	O.F.W.
7·5	100	102	92
10	100	98	88
15	100	95	85
20	100	92	82
30	100	90	80
45	100	88	77
60	100	87	76
75	100	86	75

O.N. Oil immersed, naturally cooled.

O.F.B. Oil immersed, forced oil circulation and air-blast cooled.

O.F.W. Oil immersed, forced oil circulation and water cooled.

importance and should be selected in accordance with the duty of the transformer. The unit transformer operates at about 75% full load when the generator unit is operating under normal conditions at full load. On the other hand the load of the station transformer under normal conditions is about 20-30% of its rating, and it is working near full load only for short periods during starting or emergency conditions. Fig. 26 shows the most efficient loadings at various transformer copper/iron loss ratios.

It may therefore be advantageous in some instances to reduce the iron losses in combination with increased copper losses for the station main and auxiliary transformers.

When selecting the transformer reactance, consideration should be given to values obtainable

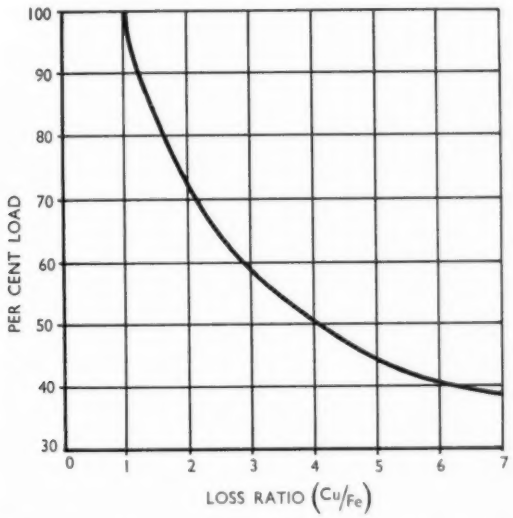


Fig. 26.—Most efficient transformer loading in relation to copper/iron losses

from a standard design. Higher or lower values can be obtained but may involve increased cost, and when high circuit reactance values are required consideration should be given to separate reactors. Typical average values of transformer reactance are given in Fig. 27.

Motors

The power station auxiliary motors range in size from fractional horse-power used for the control of valves to several thousand horse-power for driving the boiler feed pumps. Although the majority of these motors are of the squirrel cage type, their characteristics vary considerably and different types of enclosures are necessary to meet the operating conditions.

Quick starting is required, particularly for the standby auxiliaries, and with squirrel cage motors this is obtained by direct-on-line starting. The simplicity of the switching and control equipment for this type of motor together with its inherent reliability are assets which are relinquished only reluctantly for other types of drives. The specifications of the British Central Electricity Generating Board allow a starting current of 6 times full load for auxiliary motors associated with boilers, except those for the circulating water and boiler feed pumps for which the requirement is 4½ times full load.

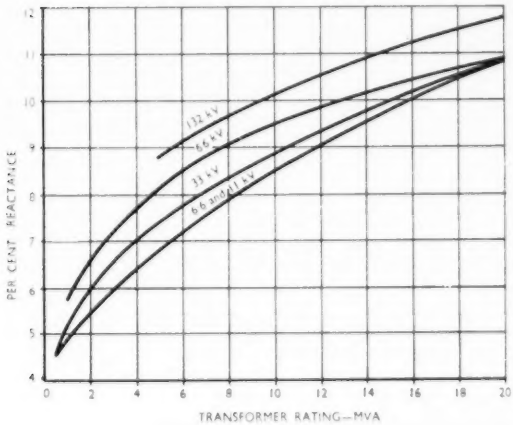


Fig. 27.—Typical average values of transformer reactance

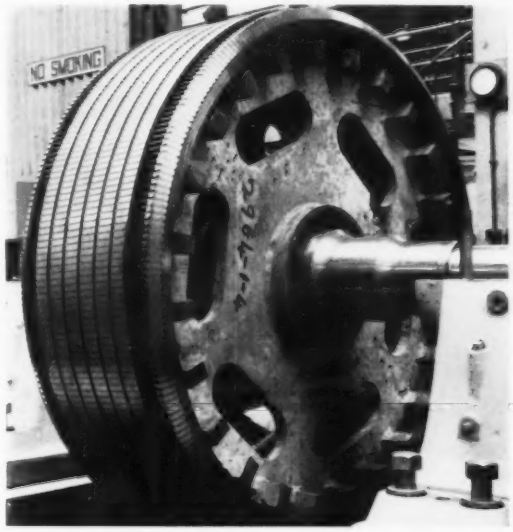


Fig. 28.—Squirrel cage rotor of 970 h.p. 297 r.p.m. motor for circulating water pump

For drives requiring variation of speed, slipring motors can be used. The starting current for these will be below twice full load and on pump drives about full load. Stable speed variation

This 2,180 h.p. (r.m.s.) 3,300 volt 500 r.p.m. (synchronous) single-reduction
West Midlands Division, No. 1 North Staffordshire Area. The single
a coal load of 6 tons in 3 mine cars in a 3-deck cage at 39·2 feet per
the winder is effected from a driver's control desk fitted with a miniature dep
Hodgart and Barclay Ltd, as s

duction winder is installed at Florence No. 3 Colliery of the National Coal Board, single pit diameter drum is 10 feet wide, and the winder is designed to raise feet per a depth of 1,590 feet. D.C. dynamic braking is provided, and control of ure depth shaft signalling windows. The mechanical parts were supplied by Fullerton, td, as su The English Electric Company

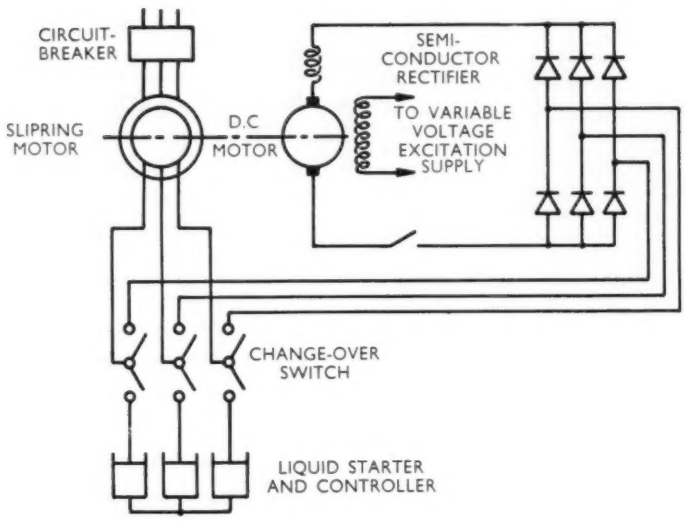


Fig. 29.—Typical arrangement for slip losses recovery

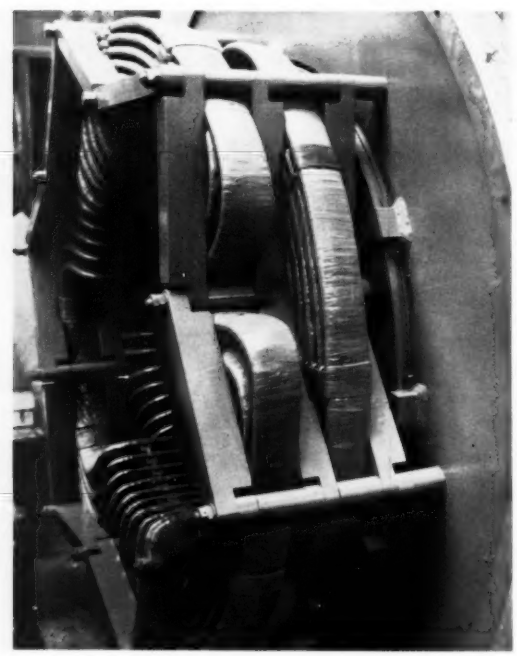


Fig. 30.—Overhang of stator winding of typical high-speed motor, showing method of clamping to withstand stresses due to direct-on-line starting

down to 50% can be obtained. These motors are now available for speeds of 3,000-3,600 r.p.m. and can therefore be applied to boiler feed pumps.

Unfortunately the efficiency of the straight slipring motor when operating at much reduced speed is low, as losses cannot be recovered from the rotor regulating resistor. Development has recently been completed however which would allow recovery of the larger part of these losses. A typical slip-losses recovery arrangement is shown diagrammatically in Fig. 29.

The extra cost of the conversion equipment may be justified, depending on the load factor, by the saving in recovered rotor slip energy capitalised over a period of its useful life. The efficiency of this type of equipment is approximately constant over the speed range at a value between 1 and 2% less than the normal full load efficiency of a slipring motor alone. This is likely to restrict economically the application to larger drives intended to operate for long periods at reduced speed. For application to feed pumps a separate d.c./a.c. motor-generator set is required, as due to the high speed of the pump it is not practicable to mount the d.c. machine on the main motor shaft.

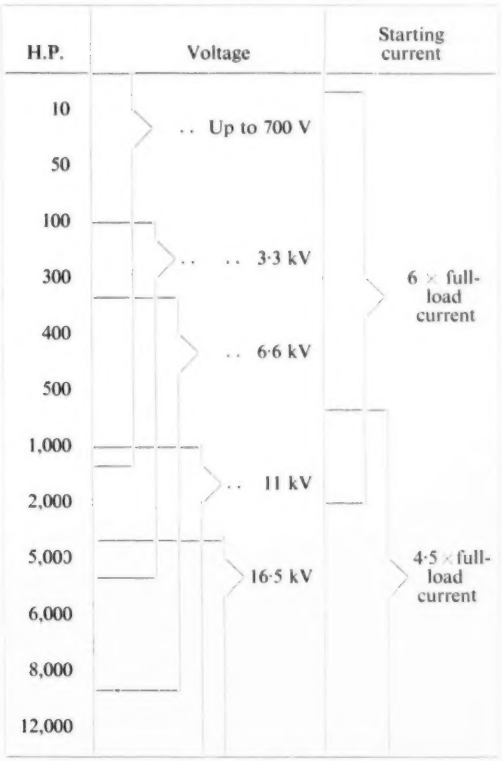
Voltage

Operating voltage in relation to rating of the motor is limited by considerations of design and manufacture, and a typical range is given in Table V. In general the higher the voltage of the motor the higher will be its cost, and as the lower voltage windings have a larger copper section they are better able to withstand the stresses imposed by direct-on-line starting.

If therefore a higher voltage is necessary to supply a small motor due to its remote location, it is more satisfactory to use a step down transformer solidly connected to the motor terminals and mounted near the motor.

TABLE V

TYPICAL VOLTAGE AND STARTING CURRENT RANGES FOR A.C. MOTORS



Voltage variations of ±5% and frequency variations of ±4% are met without difficulties. Variations over a wider range can be met by providing a larger motor, at an additional cost. As previously mentioned the motors are also designed to operate for a period of 10 minutes at a voltage reduced to 75% of nominal. Voltage dips of greater magnitude but of a transient character of 0·2-0·3 seconds likely to occur during system faults do not affect the operation of the motors.

Insulation

The selection of the type of insulation for auxiliaries motors is based on either Class 'A' or 'B' as defined in British Standard 2757. Other materials such as Class 'E' and 'H' are not normally used, as other design considerations such as maximum torque tend to determine the motor frame size and so limit the temperature rise. Class 'A' insulation is preferable for all small and medium size motors up to about 300 h.p. Above this rating, as well as for voltages from 6·6 kV onwards, Class 'B' insulation is considered more satisfactory. The higher temperature rise allowed for Class 'B' tends to result in smaller motors than with Class 'A'.

Enclosures

Selection of enclosures is based on the desired degree of protection for the motors, and this depends on the conditions existing in a particular location. Generally, drip-proof enclosures are satisfactory for indoor use when conditions are reasonably clean. Recourse to a more expensive enclosure should be made only when operating conditions are likely to justify this.

Specific problems are associated with some motors and these require individual consideration. With high speed motors of large output, as for example for boiler feed pumps, the windage noise level is high. To reduce this a totally enclosed motor is provided, with closed air circuit and either air or water cooled. A cheaper arrangement is obtained if a drip-proof motor is fitted with a special air inlet and outlet to reduce the windage noise to a reasonably low level.

Totally enclosed motors in the smaller sizes are usually fan cooled, although plain totally enclosed types are often used for short-time-rated drives as for cranes. Medium and large sizes have a closed air circuit, the air being passed through a cooler which is built either inside or outside the motor frame. These coolers can be either air cooled or water cooled. Air cooled motors are built in all sizes up to about 1,500 h.p. at any speed, but at outputs above 500-600 h.p. it becomes more economical to use water cooling.

For outdoor use weatherproof type enclosures are necessary. These can be provided readily on totally enclosed motors by suitable sealing of joints and provision for breathing. In outdoor areas reasonably free of coal dust a cheaper arrangement can be provided, usually referred to as 'ventilated weather protected'. This is basically a splash-proof open ventilated type but special provision is made in the air inlets and outlets to ensure that little moisture or water vapour is

carried within the motor. Special attention is paid to the sealing of the windings, and heaters are provided for switching on when the motor is stationary. The application of this type of enclosure is usually limited to the motors of the larger auxiliaries such as boiler fans and circulating water pumps which may be located outdoors.

Cables

Cabling, being part of the auxiliaries installation, should receive careful attention. The size of cables is determined by the maximum continuous load current. Factors influencing the heat dissipation should be taken into account, and these are : the method of laying, proximity of other cables and ambient temperature. Furthermore, consideration should be given to short-circuit rating for the smaller sizes as well as voltage drop for long lengths to remote plant. Table VI gives the recommended minimum cable sizes for various short-circuit conditions based on a fault duration of 0·3 second. These sizes can be reduced for cables protected by high rupturing capacity fuses.

TABLE VI

RECOMMENDED MINIMUM CABLE SIZES IN SQUARE INCHES FOR SHORT-CIRCUIT CONDITIONS OF 0·3 SECOND DURATION

Fault MVA	System Voltage—kV			
	0·415	3·3	6·6	11
15	0·2	—	—	—
25	0·4	—	—	—
30	0·4	—	—	—
40	0·6	0·1	—	—
150	—	0·25	0·15	0·1
250	—	0·4	0·2	0·15
350	—	—	0·3	0·2
500	—	—	0·4	0·25
750	—	—	0·6	0·4

For power cables the paper insulated lead sheathed type is generally used. Three-core cables are satisfactory up to about 0·5 sq in. conductor size and these are generally armoured. For larger sizes single-core unarmoured cables are preferable on account of handling during erection and improved rating. Armouring is desirable on all three-core cables to reduce their vulnerability to mechanical damage. The armouring is usually left bright for indoor installation, but sometimes fire-resisting serving is provided in fire-risk locations. Serving is provided for cables laid direct in the ground.

Special consideration should be given to the routes of unarmoured cables within the power house, and provision of underground tunnels or covered concrete trenches is desirable to reduce the likelihood of mechanical damage.

For small loads up to about 30 h.p. mineral insulated cables are often used due to the ease and economy in installation. This type of cable can operate in high temperatures and is very robust mechanically.

Covered trenches and ducts should be included in the civil construction to afford obstructionless cable runs in basements of boiler and turbine houses. Under operating floors and on upper levels, cables are run on prefabricated sheet metal racks. The type of fixing employed should facilitate ease of erection of cables in any desired order and also allow for probable future addition or removal.

Careful planning at an early stage of power station design is necessary to ensure good results from the engineering and aesthetic point of view.

CONCLUSIONS

The trend towards large generating units of 200 MW and above operating at advanced steam conditions is now well established. For very large

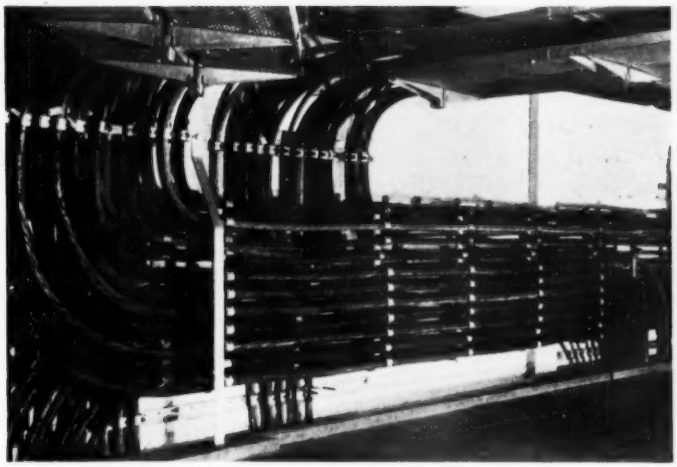


Fig. 31.—Typical arrangement of cabling in power station

Photograph by courtesy of British Insulated Callender's Construction Company Ltd.

interconnected systems the general level may be established in the near future at about 400 MW unit size with the largest sets approaching 800 MW.

The steam conditions are likely to level at 2,300 p.s.i.g., 1,050/1,050°F single reheat, although development in the supercritical range with double reheat cycle is well advanced.

In the field of nuclear stations the steam conditions obtained at present are low. Intensive research and development are however being carried out and it appears likely that within the next few years much higher steam conditions will be reached, resulting in higher efficiency and increased output per reactor.

Electric drives for all auxiliaries are now generally accepted for conventional as well as nuclear stations, with special attention being given to boiler feed pumps and coolant circulators for reactors. Consideration is also being given to means of driving the boiler feed pumps from the main generator shaft or by a separate turbine. The arrangement to be adopted is of course dependent on economical considerations and on the development of reliable electrical drives with speed control.

The unit auxiliaries system can be advantageously extended to the largest generating units now envisaged. Sectionalisation of auxiliaries supply is justified for cross-compound units, but with tandem units a straight unit system is preferable due to its simplicity, even at a cost of increased short-circuit rating of switchgear.

The auxiliaries load associated with very large units above 200 MW cannot be conveniently accommodated on a two-voltage auxiliaries system, and a three-voltage system, such as 11 kV, 3·3 kV and L.V., provides a solution.

The equipment at present available or under development can meet the requirements for auxiliaries for the largest generating units contemplated. Further development is necessary however in electrical drives with economical speed control for large boiler feed pumps for conventional steam stations and coolant circulators for nuclear stations.

Acknowledgments

The author wishes to acknowledge the assistance and contributions of members of the Committee for Power Station Auxiliary Electrical Systems and Equipment, and members of the following departments :—

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Switchgear Engineering
Switchgear Sales and Contracts
Steam Turbine Design
Transformer Sales

Industrial Television

By J. E. H. BRACE, B.Sc., Chief of Industrial Television, Broadcasting Division, Marconi's Wireless Telegraph Company Limited.

It is the author's belief that television will become, during the next few years, a widely used and important industrial tool. Its success must depend however on close co-operation at this stage between user and manufacturer, each of whom will thus need a proper understanding of the problems involved. The aim of this article is to indicate a few of the genuine applications so far established and to describe how one manufacturer, Marconi's Wireless Telegraph Company, has approached the questions of equipment design and utilisation.

TELEVISION is, without question, one of the most fascinating developments of the last fifty years, and might even take its place in history as one of mankind's major achievements. Although now accepted as part of everyday life, it is in fact an extraordinary feat to sit in an armchair in Liverpool and become part of the audience of an opera production in Vienna or a sporting contest in Stockholm ; such an idea was well beyond the imagination even of Jules Verne whose prophetic vision foresaw many of the remarkable inventions of the twentieth century.

The uniquely satisfactory nature of television as a communications medium is evidenced by the almost alarming manner in which it is superseding most other entertainment media. Faithful pictorial representation, instantaneous transmission over virtually unlimited distances, simultaneous reception at as many and as widely separated points as required ; no other medium exists which combines all these important characteristics. Even colour may now be included, and the addition of a third dimension is a well-established technique.

With all these advantages it was inevitable that television would sooner or later be applied to more useful tasks than mere entertainment, and it is perhaps surprising that this evolution did not come about earlier. However, whilst high-definition television as such has been in existence for well over twenty years, early equipment was of sufficient complexity, fragility and cost as to preclude any idea of its employment elsewhere than in the only industry, entertainment, where these factors were of negligible importance. Little direct development of television was carried out during the war, but immediately it was possible to do so several companies devoted effort to the simplification and improvement of equipment, in many cases with the object of producing a system suitable for industrial and other private uses.

The major problem to be overcome was posed by the absence of an entirely suitable camera tube. The tubes, such as the Image Orthicon, used for broadcast television were too complicated and costly and did not readily lend themselves to simplification or miniaturisation. The first tube used for industrial television was the Farnsworth Image Dissector but, although superficially attractive on account of its simplicity and inherently long life, this tube was found to be hopelessly insensitive for the majority of applications. The position was radically improved in 1950 with the development of the Vidicon, a tube which, unlike all previous types, exploits the principle of photoconduction. However, the first examples of the Vidicon were of poorer sensitivity than had been anticipated from theoretical considerations, and considerable further work was done during the following two years to overcome this, unfortunately without any real success.

In about 1952, therefore, the Vidicon was accepted as it stood and a number of simplified television systems designed around this tube appeared on the market. The first demonstrations were attended by much press publicity of a sensational and largely

misleading nature, mostly unwelcome to the manufacturers, and cautious interest tempered with scepticism on the part of industry. During the six years which have since elapsed three distinct phases are discernible. In the first, a few manufacturers of repute were offering relatively expensive equipment clearly showing its studio television parentage, the limited success of which was attributed to the high cost. This led to the second phase, during which it was considered that if the cost was low enough equipments would be sold in thousands more or less 'over the counter', and a number of very simple and cheap designs appeared on the market, particularly in the United States. The degree of success during this phase was relatively even lower than during the first. The third phase, which began quite recently, has been marked by the sudden awakening of several potentially large users and a period of re-thinking by the major manufacturers. The results of this six-year period may be summarised as follows :—

(1) Requirements for different applications vary widely and must be carefully assessed before any equipment is installed.
(2) Initial cost of equipment is of less importance than its inherent reliability, and the necessary standard of reliability can only be achieved by designing equipment to industrial standards.
(3) When properly designed and installed, television can perform a number of extremely useful tasks in industry. Industrial television has grown up and is here to stay.

Applications

As might be expected, the majority of installations so far made in Britain have been for government departments and nationalised industries, and these have, of course, provided valuable experience from both the manufacturer's and user's point of view. In particular, the Central Electricity Generating Board, the Atomic Energy Authority and the Ministry of Supply now consider television as an everyday tool and have purchased appreciable quantities of equipment.

The Central Electricity Generating Board has established two major applications and is experimenting with others. The first major application involves the observation of furnace flame conditions and has been the subject of numerous trials and

Fig. 1.—Special camera mounting for furnace flame viewing

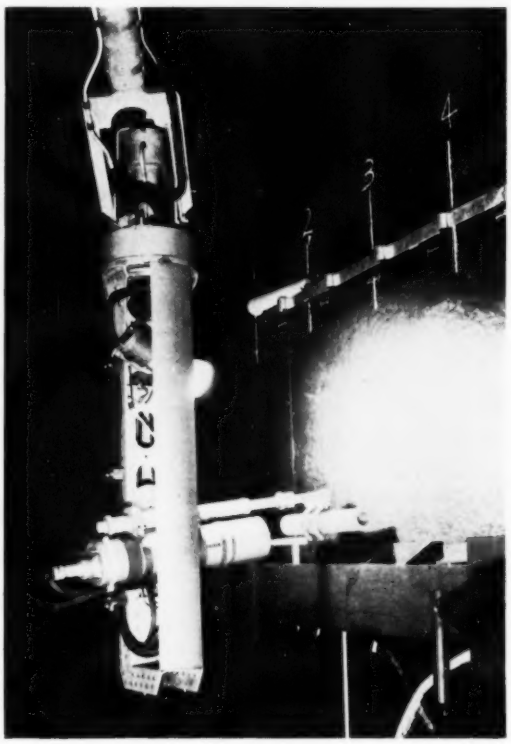
experiments over the past few years, the first of which took place at Little Barford power station in 1954. Unfortunately, although of indisputable value, most of these tests were inconclusive owing to the fact that suitable apertures at the required positions are normally not available in existing boilers so that the results obtainable under the conditions of a properly planned installation are largely a matter of conjecture. However, in 1954 the British Electricity Authority, as it then was, decided to go ahead with a full-scale installation at Willington 'A' power station then in the planning stage.

The boilers at Willington 'A' are of International Combustion manufacture and, being corner-fired in accordance with the maker's normal practice, it was decided that the best position for the camera would be at the top of the boiler looking straight down into the furnace, which should provide a good view of the flame

vortex under most combustion conditions. Apertures of approximately 10 inches in diameter had to be provided in the boiler casing, which involved considerable tubing displacements, and a special camera mounting had to be devised to provide adequate protection against the high level of radiant heat and the high ambient temperature. This mounting, shown in Fig. 1, comprises a double glass window, water-cooled, which acts as an infra-red filter, and a protective case for the camera. Air from a centrifugal blower is introduced at the front of the case to cool the camera and is released through a non-return valve at the other end. Part of the air supply is used as a blast across the furnace side of the glass window to keep it clear of fly-ash. The assembly is bolted direct to the boiler casing but is thermally isolated from it by a layer of asbestos board. Ancillary equipment includes the blower and filter, a water pump and commonly a heat exchanger and header tank to make up a closed-circuit system, supply failure detectors and alarms and so on, in addition, of course, to the camera control unit and the viewing monitor which are normally mounted in the boiler control panel.

The Willington installation has only recently been put into operation so that its usefulness has still to be assessed. In the meantime, considerable work has been done with front-fired boilers of the Babcock & Wilcox type, culminating in the design of a furnace viewing periscope by the British Iron and Steel Research Association and Foster Instruments Ltd, for Babcock & Wilcox Ltd. This periscope, described as 'panoramic', provides a rectangular field of view of approximately 45 degrees by 90 degrees and was specifically intended for insertion into a front-fired boiler in the front wall immediately above the burners, the flames from which thus appear in a straight line across the width of the image. Foster Instruments have since produced variations of the original device to suit different requirements, and these will be installed in several new stations.

The Babcock & Wilcox set-up was originally installed at Barking 'C' power station and is shown in Fig. 3. The periscope is mounted on a pneumatically operated carriage for ease of insertion and withdrawal and this is coupled with a photo-electric flame-failure detector and a flow-controlled



Photograph by courtesy of Sir W. G. Armstrong Whitworth Ltd.

Fig. 2.—Robot with Marconi television camera, designed by the Atomic Energy Authority for removing spent radio-active cartridges from atomic piles

switch in the cooling-water line to the periscope jacket. The television camera is supported by a bracket at the rear end of the periscope. The overall diameter of the periscope is such that a 4-inch aperture in the furnace wall is sufficient. Operational experience with this installation indicates that faulty ignition or operation of burners can be immediately detected and that the normal hazards associated with the lighting-up of pulverized fuel furnaces are appreciably reduced. A second installation of this type is at Poole power station on an Associated British Combustion oil-fired furnace, and others of both the types described are in the planning stage.

The second of the two applications so far established by the Central Electricity Generating

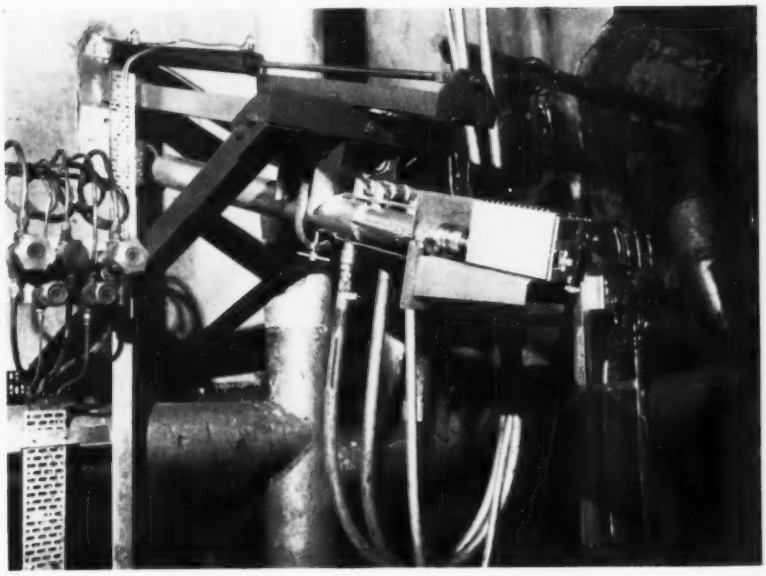


Fig. 3.—Marconi camera fitted with Babcock-Foster furnace-viewing periscope, at Barking 'C' power station of the Central Electricity Generating Board

Board concerns the observation of drum water-level gauges on power station boilers. These gauges are situated at anything up to 150 feet above the level of the control panel and must be kept under continuous observation. Various devices have been developed to provide a remote level indication at the control panel but all suffer the disadvantage that a fault in the system could conceivably result in a false indication. Such devices must therefore be duplicated and also periodically verified by a responsible operative who is thus obliged to climb to drum level several times during each shift. The simple periscope used in older power stations provides only a very small image and generally necessitates a journey away from the control panel, its employment in the larger and more complex modern station being virtually impossible. Television, of course, provides an excellent answer to this problem, as it ensures correct information and provides it at the exact point required.

The Atomic Energy Authority was among the first users of industrial television in Britain; in fact in the atomic field the technique is regarded as almost indispensable. This is no doubt due, in part, to the fact that atomic energy is the only major branch of industry to have come into being since the perfection of television. Applications include procedures that cannot be achieved by any other means, such as the internal inspection of atomic piles, and others in which television plays an important role in reducing occupational hazard, such as the remote manipulation of dangerous materials. Television is used to facilitate the removal of spent slugs which have become lodged at various points on the rear face of the pile core at Windscale in Cumberland. The Industrial Group of the United Kingdom Atomic Energy Authority has designed a remotely controlled manipulator, the head of which, shown in Fig. 2, carries a Marconi television camera and can be lowered into the space between the core and the rear wall of the pile and then luffed out to any desired point on the core face, the lodged slugs being detected with the camera and removed with the grab.

For certain applications of this type a normal two-dimensional image is insufficient and this has necessitated the development of special three-dimensional equipment consisting essentially of two separate television cameras side by side, representing the two eyes, and two separate displays so disposed

that each eye sees only the image from the appropriate camera. This can be achieved by mounting the two display monitors in a common cabinet, one being horizontal and the other vertical, so that their screens are adjacent and at right angles to each other, thus facilitating the superimposition of the two images by means of a semi-silvered mirror placed symmetrically between them. Each screen is covered by a sheet of polaroid, the directions of polarisation being mutually perpendicular. The observer sees the correct image with each eye by means of appropriately polarised spectacles. Such a system, developed by Marconi's, has been supplied to the Atomic Energy Research Establishment at Harwell.

Various uses for television have been found by the Ministry of Supply but many are of a secret nature and cannot be described. In general terms, a wide range of activities is covered including the manufacture of explosives, the testing of gas-turbine engines and rocket motors, the testing of aircraft models in wind tunnels, and so on. The three Service Departments, British Railways and the National Coal Board are likewise all giving active consideration to the various ways in which they can employ television.

In the sphere of private industry in Britain it is the Steel Industry which up to now has been most active in experimenting with television, and many successful installations are in existence. Again, this is to a great extent due to the nature of the industry in which a large number of 'natural' applications are readily discernible even to an outsider.

The first convincing demonstration occurred a few years ago at the Margam works of The Steel Company of Wales. The breaking of one of the manipulator claws on a slabbing mill threatened to close down the mill when attempts to use a crane to turn the slabs over failed due to difficulty in aligning the crane hook. An urgent request for a television camera to provide the operator with a better view was promptly answered and the equipment was on site and installed within 12 hours of the request. Production at only a slightly reduced rate was continued by this means until the manipulator was repaired. Since then The Steel Company of Wales has installed television to assist in the operation of a hot-strip coiler (the control pulpit of which is shown in Fig. 4) by giving the operators additional advance warning of the arrival of a strip. In an experimental installation a television camera is being used with great success to detect scarf on the underside of the strip as it comes off

Fig. 4.—Television monitor at the coiler control panel in the hot strip mill at the Abbey Works of The Steel Company of Wales, Port Talbot

the mill. A new and complex installation involving 15 cameras facilitates the operation of a remotely controlled ingot buggy which receives ingots from the soaking pits and transfers them to a second buggy ; this, incidentally, is the first steel-making installation in Britain actually designed to incorporate television.

At the Scunthorpe works of the Appleby-Frodingham Steel Company cutting instructions are passed to the cold shear operators by television. Increased efficiency and a reduction in the personnel associated with the process have resulted.

The production of large-section welded pipes is carried out with the assistance of television at the Coatbridge works of Stewarts and Lloyds. An ingenious arc-welding machine, designed and built by Quasi-Arc Limited, carries a welding head and a television camera on the end of a boom which is inserted into the pipe. The seam can thus be inspected as it is welded and satisfactory welding is assured.

Other British steel companies using television include the Round Oak Steel Works near Birmingham, Richard Thomas & Baldwins at Ebbw Vale, the South Durham Steel & Iron Company at West Hartlepool, and Steel Peech & Tozer at Sheffield. Television has also been applied, either in the United Kingdom or abroad, to the control of slab re-heat furnaces, continuous casting processes, pipe expanding and pipe sawing machines, and scrap handling.

In other industries progress has been much slower. Numerous applications have been tried in the aircraft industry, for example, but so far few permanent installations have been made. There is considerable interest in the possible use of television in connection with flight testing, particularly if information can be transmitted to a ground station during flight. Apart from the obvious applications in connection with explosives manufacture, virtually no applications have yet been established in the chemical industry.

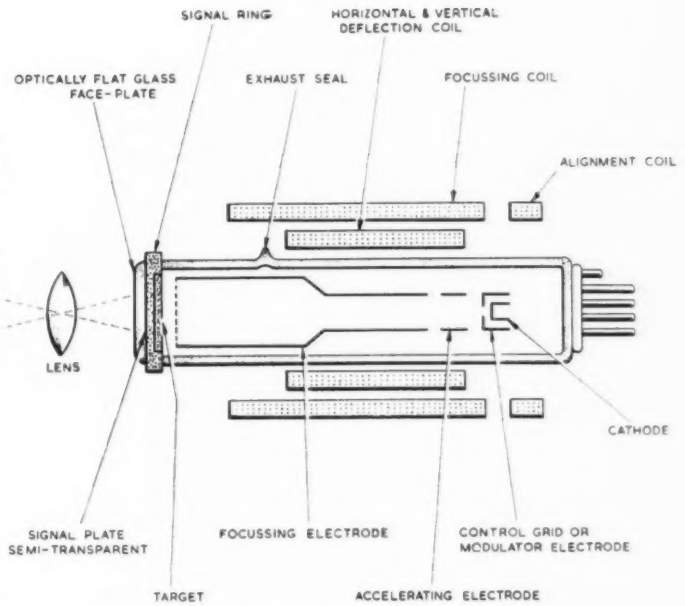


Fig. 5.—Cross section of Vidicon pick-up tube

Whilst the application to plant security has met with considerable success in the United States, the author is not aware of any such installation in Britain.

The transmission of documentary information by television in banks, insurance companies and other large office organizations is still at the experimental stage but promises to be a major application in the future.

The Vidicon

It was with the development of the photo-conductive tube, the first successful design of which appeared in 1951, that industrial television became a really practical possibility. This tube, the Vidicon, combines nearly all the theoretical requirements for a successful industrial pick-up tube and forms the basis of most current designs of industrial television equipment. Sensitivity and definition are less dependent on the size of the photo-sensitive surface than with photo-emissive tubes such as the Image Orthicon, and this results in a

tube of satisfactory performance and very compact dimensions. It is also of very simple and rugged construction, may be operated over long periods without attention, is capable of dealing satisfactorily with a very wide range of incident light levels and has an inherently long life.

A cross-section of the tube is shown in Fig. 5. It consists of a tubular glass envelope, approximately 1 inch in diameter and 6 inches in length, closed at the rear end by the connection pins and at the front end by a flat glass plate. On to the inside of this plate is deposited a thin, transparent metal layer, the signal plate, electrical connection to which is made by a metal ring sealed through the envelope.

The photo-conductive surface, or target, is in turn deposited on the signal plate. This material is a good insulator in darkness but becomes progressively conductive with increasing illumination.

An electron gun at the other end of the tube projects a fine beam of electrons towards the target, the intensity of this beam being controlled by the voltage applied to the control electrode in the gun. A magnetic field, produced by a coil or a set of bar magnets surrounding the tube, coupled with an electro-static field, produced by the application of an adjustable voltage to the cylindrical electrode inside the envelope, permits the electron beam to be focussed to a fine spot at the target. The cylindrical electrode is closed at the target end by a fine mesh, the wall screen, which provides a uniform decelerating field for the electron beam and thus ensures that the electrons impinge on the target at very low velocity. This is to prevent secondary emission from the target which would give rise to serious image defects.

Voltages of suitable waveform applied to the horizontal and vertical deflection coils surrounding the tube cause the electron beam to scan the target in the normal manner.

An adjustable positive bias voltage of 10-100 volts is applied through a high resistance to the signal plate and thus to one side of the target, the signal plate being also connected to ground through a high load resistance.

With no incident light the target is a good insulator and the cathode side is therefore quickly charged to cathode potential by the scanning beam, a state of equilibrium being reached when all scanning electrons are repelled by the target and collected by the wall screen. A potential difference will thus exist between the two sides of the target due to the applied bias voltage.

If a luminous image is now focussed on to the target the conductivity of each illuminated element will increase in proportion to the intensity of incident light and will thus cause the voltage at the cathode side to start rising towards the bias voltage. Thus, at its next arrival the scanning beam can deposit electrons at that point, and this will cause a momentary decrease in voltage at the signal-plate side due to current flowing in the load resistance. In effect, therefore, the voltage on the signal plate will fluctuate as the scanning beam moves across the target, and it is this voltage fluctuation which constitutes the output 'video' signal from the tube. It should be noted that the charge at any given point on the target is accumulated over the whole of the interval between successive passages of the scanning beam, and this storage effect contributes very significantly to the sensitivity of the tube. A Vidicon tube, Type P.810, manufactured by the English Electric Valve Company, is shown in Fig. 6.

Equipment

More than twenty-five manufacturers throughout the world now produce television cameras for industrial use, a clear indication in itself of the rapidly growing interest in the technique. Nearly all are based on the Vidicon pick-up tube or its equivalent. The most usual arrangement consists of a camera of minimum dimensions, a camera control unit containing scanning circuits and power supplies, and a separate monitor the screen size of which varies within the range 5 inches to 27 inches. Certain designs combine camera and camera control unit or control unit and monitor, but this usually constitutes a restriction on flexibility. An early tendency to use modified or unmodified domestic receivers as monitors has largely been abandoned due to the normally poor reliability of such devices under industrial conditions, and most manufacturers now offer specially designed industrial monitors. Unfortunately many users

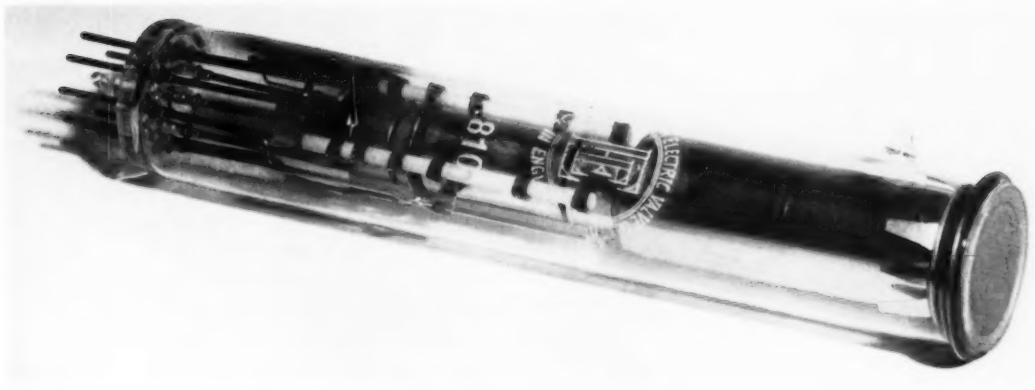


Fig. 6.—Vidicon pick-up tube

have difficulty in understanding the considerable difference in price that this necessarily involves.

The latest Marconi equipment, recently introduced, is shown in Fig. 7. This equipment is of very advanced design and represents the results of several years' experience and assessment in the field.

The channel comprises a camera and a camera control unit connected by a multi-core cable which may be up to 1,000 feet (300 m) in length. The camera is of cylindrical shape and measures 4 inches (10 cm) in diameter by 11 inches (28 cm) in length. It is a sealed unit and contains only two valves in addition to the Vidicon tube and its scanning yoke. The complete yoke and head amplifier assembly is movable along the camera axis for the purposes of optical focussing, this movement being controlled by a threaded shaft which projects out of the back of the camera. This shaft, which is normally provided with a knob, can also be driven by a motor if remote actuation is required ; the motor is contained in a small unit which can be mounted on the back of the camera and increases its overall length by 3 inches (7·5 cm).

The camera control unit is housed in a rectangular case suitable for free-standing use or rack-mounting, it being possible to mount two side by side in a standard 19-inch rack. The unit houses the power supplies, scanning waveform generators, Vidicon protection circuit and final video amplifier. Also incorporated are an auto-

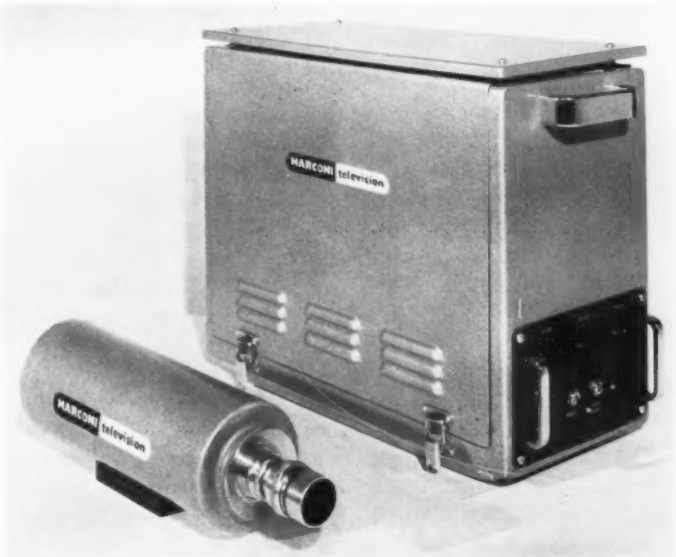


Fig. 7.—Marconi industrial television camera channel

matic sensitivity control circuit, which provides automatic compensation for variations in scene illumination over a wide range but which may be rendered inoperative if required, and an R.F. oscillator and modulator to provide a modulated R.F. carrier output in addition to the 1·5 volt composite video output. The R.F. carrier frequency is normally fixed at 20 Mc/s but may as an alternative be tunable over Band 1. Using a suitable low-loss coaxial cable the 20 Mc/s signal may be transmitted over a distance of 8,000 feet (2,400 m) without additional amplification.

Special design features are :—

(1) Of the total of 17 valves, 13 are of a single type of 'ruggedised' double triode, with an estimated life of 10,000 hours.

(2) All valves are operated well within their ratings and, in all critical circuits, with stabilised mean anode current which renders performance semi-independent of reduced emission and variations in valve parameters.

(3) Printed wiring is used for all circuits except the power supply.

(4) The main operational controls are mounted on a separate small unit normally plugged in to the front of the control unit but which may also be 'remoted' on a multicore cable up to 500 feet (150 m) in length.

(5) The line timebase is free-running and can be adjusted to give either 405 or 625 lines when the equipment is operated from a 50 cycle supply (the frame timebase being locked to the supply frequency or) 525 lines when the equipment is operated from a 60 cycles supply. Provision is also made to drive the two timebases from an external source if an interlaced scan is required.

(6) Synchronous operation of several channels is provided for. Timebase and R.F. carrier outputs from the channel nominated as 'master' drive the timebases and R.F. oscillators of the slave channels. This feature eliminates the need for readjustment of the controls of a common monitor as cameras are switched in a multi-channel installation.

(7) The equipment is designed to withstand vibration and mechanical shock of an appreciable order.

(8) A horizontal definition of 600 lines is obtainable using the 625-line scanning standard.

(9) Carefully designed low-noise amplifiers enable usable pictures to be obtained with a suitable lens at illumination levels well below 10 foot-candles.

A 14-inch display monitor designed to a similar specification is available for use with this camera channel. A range of accessories is also in course of preparation and will include such devices as weatherproof cases, a flameproof camera case, a remotely controlled twin lens turret and a remotely controlled pan and tilt head.

Installation

The equipment described under the previous heading represents a conscientious attempt to produce an electronic device which will withstand the arduous operating conditions imposed by an industrial environment and which will operate satisfactorily for long periods unattended. Whilst a very high degree of reliability is thus inherent in the equipment, it is obvious that it will only be obtained in practice if due precautions are taken during installation.

The installation engineer will ensure that the equipment is operated within its specification in respect of mains voltage variations, ambient temperature, vibration and so on. A supply voltage stability of $\pm$ 5% or better is necessary, this being imposed by the necessity of maintaining valve heaters within these limits for maximum valve life. Where such a supply is not available a line voltage stabiliser will be required, and care should be taken to ensure that a suitable type is selected. Rapid variations require an electronic stabiliser and slower variations are normally dealt with satisfactorily by the simpler saturated-core device. In either case there is a wide diversity of types available, not all of which give an output of satisfactory waveform for television equipment.

Maximum and minimum ambient temperatures should be measured at the proposed site for each item of equipment and checked against equipment ratings which are respectively -20°C minimum

to 45°C maximum for the camera and 50°C maximum for the camera control unit and monitor. Low temperature is seldom a problem in Great Britain but it is frequently necessary to provide protection against high ambient temperature, and various methods may be adopted. Equipment should also be protected against dust, humidity, corrosive vapours and excessive vibration. It is, in fact, quite possible for the cost of accessories to equal or even to exceed the cost of the television equipment, but it cannot be too strongly emphasised that money saved initially at the expense of adequate protection of equipment may subsequently be spent many times over in excessive maintenance costs.

Conclusion

Television has developed to a stage where it can, with wise selection and installation, be confidently incorporated in a diversity of industrial processes and perform vital and useful tasks. Important developments in equipment for specialised applications can be expected during the next decade with the emphasis on miniaturisation, increased performance and colour reproduction. There can be little doubt that the technique has a big future in industry.

Automatic Machine Controls at the Brinsworth Mill of Steel Peech & Tozer

By A. P. BAINES, A.M.I.E.E., Metal Industries Division.

The December 1958 issue of this Journal contained an article on the electrical equipment installed by The English Electric Company at the Brinsworth Mill of Steel Peech & Tozer. This mill forms one illustration of the use of modern control techniques to obtain greater and more economical production in the steel industry. The present article describes in more detail the automatic controls provided for the hot strip mill.

A STUDY OF THE PROBLEMS involved in the application of electric drives to industry indicates that a limit to high production is often caused by the inherent characteristics of the driving motor and its power source. Closed loop control techniques have, over the years, been evolved to compensate for undesirable machine characteristics, but it is only in recent years that new control components, such as magnetic amplifiers, which are suitable for industrial applications, have been developed to allow the fullest application of these techniques.

In applying such control techniques it is necessary to determine the requirements of a particular drive, and then analyse the effect that the inherent characteristics of the most suitable driving motor and power source for the application have upon these requirements. By applying a suitable closed loop control the effects of any undesirable characteristics may then be eliminated or reduced.

The intention here is to describe the application of closed loop controls at the Brinsworth hot strip mill and to show the advantages to be gained from their use. This mill consists of a number of stands, their speeds and roll gaps being so adjusted that a slab, by passing through each stand in turn, is reduced in thickness to form a coil of thin strip. Fig. 1 shows diagrammatically the relative positions of the stands and the change in length of the product as it passes through the mill from the furnace to the coilers. By considering the change in rolling conditions as the product proceeds through the mill, the difficulties of control without the use of closed loop controls become apparent. These difficulties, and therefore the necessity for applying closed loop controls, increase as the rolling conditions change, becoming more acute on the finishing stands where the product is being rolled at its highest speed and is more susceptible to damage.

Edger and First Roughing Stand

At the horizontal edger and the first roughing stand the product is short in length and allows the stands to be so situated that the drives are independent of one another, the product leaving one stand before entering the next. There is no neces-

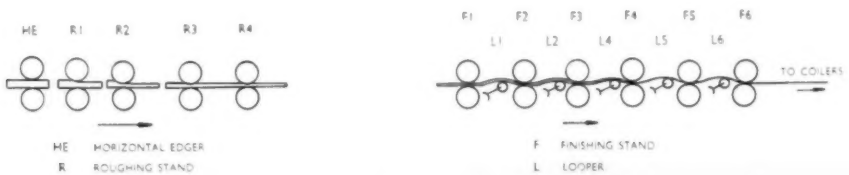


Fig. 1.—Relative positions of drives at the Brinsworth hot strip mill

sity for accurately maintaining speed or for applying anything but the simplest of control schemes. Advantage can be taken of a motor and flywheel to supply the heavy but short duration loading on the drives.

Second Roughing Stand

The conditions at the second roughing stand differ from those at the preceding stands in that the product being rolled presents a longer duration load to the drive, and so prevents economy being gained from the use of a flywheel drive. Advantage is instead taken of a synchronous motor drive with a closed loop power factor control, the action of which is to monitor and maintain at unity the power factor of the supply to the motor by automatically adjusting the excitation. The rate of response of this system is made rapid by the use of a magnetic amplifier with ample capacity for forcing the motor excitation under transient conditions. This control application is an example of the use of a closed loop technique to improve the efficiency of a standard form of drive which in other respects fulfils the rolling requirements.

Third and Fourth Roughing Stands

The rolling conditions on roughing stands 3 and 4 differ again, in that the length of product and considerations of space necessitate positioning these stands so that the rolled product is in both at the same time. It therefore becomes necessary to control the speed relationship of these stands to obtain correct rolling conditions. The system used at Brinsworth employs a synchronous motor drive for Stand 3 with a power factor control similar to that used on Stand 2, and a variable speed d.c. drive for Stand 4. The latter comprises a closed loop rectifier-fed armature voltage control which coupled with a close regulation machine with field weakening speed adjustment provides a simple means for controlling the speed relationship between stands.

However, one disadvantage of this arrangement is the inability of the rectifiers to allow regeneration, and the possibility of overvoltage on the motor when reducing the motor speed by the field weakening control. This is of particular concern when changing speed with the mill unloaded, when excessive rates of change of speed must be limited by limiting the speed of the motor-driven field rheostat. Although this is a necessary precaution with the mill unloaded, it is not so necessary with the mill loaded, when excess power can be absorbed by the load. Therefore, to improve the operating characteristics of the mill a load relay is used to detect the presence of load, and in so doing automatically makes available to the mill operator a faster acting field control.

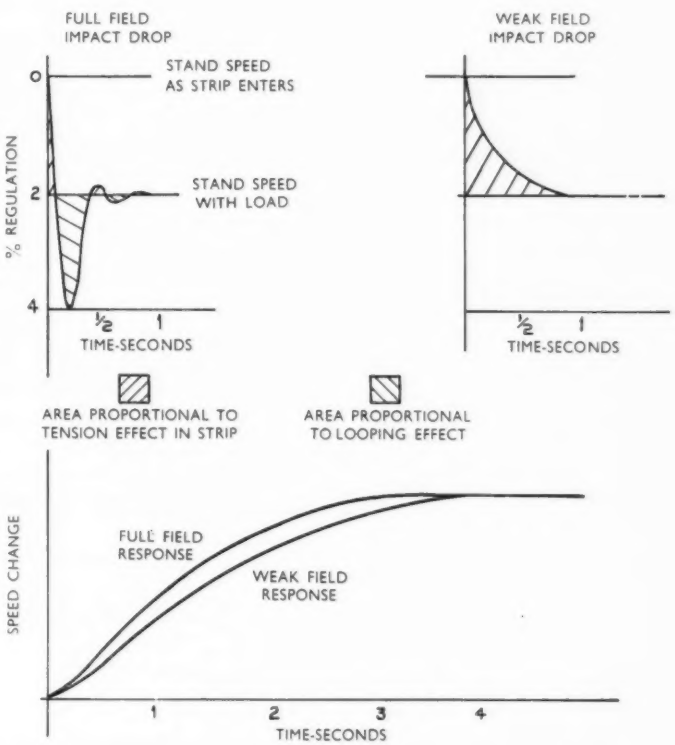


Fig. 2.—Impact drop characteristics and responses to changes in speed at base and top speed without speed control

Fig. 3.—Motor room, showing five of the six finishing mill motors in the left foreground and the magnetic amplifier cubicles on the right

Further to assist the operating conditions of these stands, a compounding control has been made available to the operator. This is used during trial rolling when the action of the voltage control may, in attempting to maintain an incorrect speed setting, cause excessive overloading of Stand 4. The action of the compounding control allows a signal proportional to load current to be fed back to suppress the rectifier voltage control and impart a drooping speed characteristic to the motor.

Finishing Stands

As already mentioned, the problems associated with the application of electric drives to continuous hot mills become more acute when considering the finishing stands. It is on these stands, which produce a high standard of product, that even a comparatively small change in rolling conditions can cause not only off-gauge products but also time consuming hold-ups in production. The dominant factors affecting the controls are, the high speed of production, particularly on the last stand of the train, the fact that the product is in all stands at once, and the inability of the product to transmit excessive torque between stands.

Consider the sequence of events as the product enters the stands. On entry, the impact of the piece on the drive will cause the speed to drop and then recover to a value dependent upon the loading and regulation characteristic of the drive. While the speed of the drive is below the required value a loop of material will be thrown in front of the stand, and while above the required speed the loop will be taken up, or if not present, will cause tension in the material. Tension represents a force tending to reduce the cross sectional area of the material and will cause an off-gauge product, particularly on the thinner gauges being rolled. As rolling proceeds, mismatching of stand speeds will cause either excess strip to be fed between stands and hence the growth of a loop, or continual stretching of the piece to breaking point. Whilst it is evident that the formation of a loop is more desirable than stretching, a further advantage of a loop is that it provides a visual indication of correct or incorrect speed setting. However, an excessive loop must not be allowed to form, for if it doubles over and attempts to enter a stand, not only will the rolls be damaged but valuable production time will be lost in clearing the pile-up of material.

The purpose of the control system is firstly, to overcome the detrimental effects caused by impact speed drop as the material enters the mill, secondly, to provide a means for rapid manual speed adjustment, and thirdly, to maintain the correct rolling conditions when once set.

In the past the simplest form of drive used on continuous hot mills employed close regulation d.c. machines, with manual speed control by varying

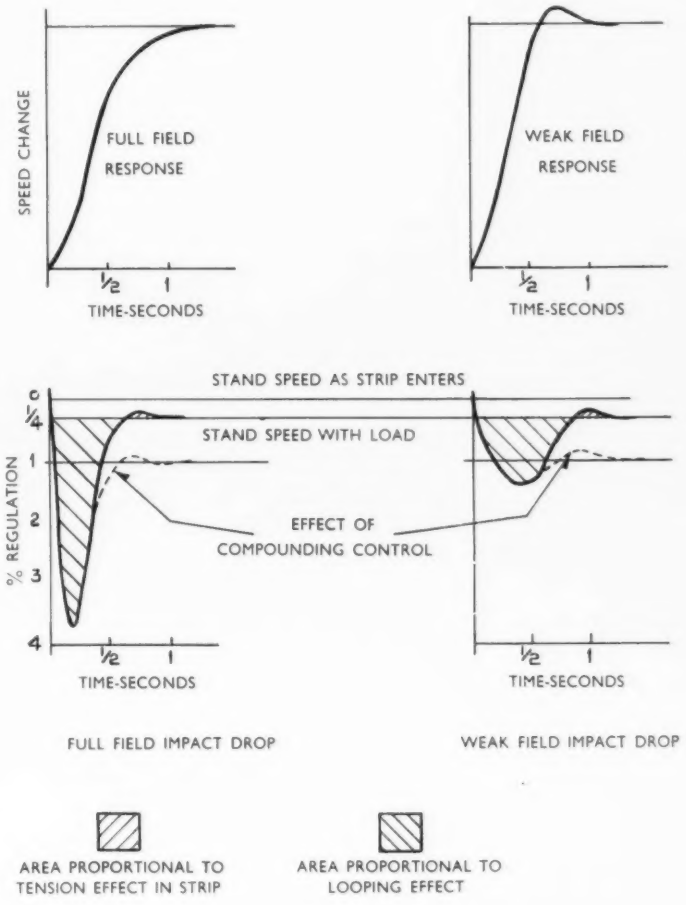


Fig. 4.—Impact drop characteristics and responses to changes in speed at base and top speed with speed control

the motor field excitation. Although quite adequate for comparatively slow-speed mills, such a method has the disadvantages of an inherently slow response when changes in speed are desired, variations in speed setting due to temperature changes in the motor field, and an unsatisfactory speed characteristic when the product enters the mill. Fig. 2 shows the characteristic of the Brinsworth finishing-mill motors if this simpler form of control were used. When running at base speed with full field excitation, the speed characteristic or impact drop as the product enters the mill can be considered satisfactory ; a momentary tension effect is followed by a drop in speed to form a loop of material. However, at top speed the impact drop is such that tension occurs in the strip with no looping effect to relieve that tension. Such an effect would require immediate correction by manual speed adjustment. Also shown in Fig. 2 are the responses of motor speed when attempting to make such a correction. Considering that the product may be entering the stands at any speed up to 50 ft a second, a sluggish response would prevent the operators from making any necessary changes in speed quickly and effectively.

To overcome these disadvantages a form of closed loop speed control is desirable. Two methods in use employ either separate supplies to each motor armature or a common armature supply with buck and boost exciters in series with each motor. A third method, and that adopted at the Brinsworth mill, represents a more economical form of closed loop control, allowing the use of a common armature supply to the motors, with the speed control acting upon the motor fields. Five of the six motors with their control equipments are shown in Fig. 3.

The use of a closed loop control system allows rapid speed changes to be made, as indicated by the responses to changes in speed shown in Fig. 4. Also shown in this figure are the impact speed drop characteristics, which when compared with those in Fig. 2, indicate the improvement that can be obtained, particularly at top running speed. Not only is it possible with such a control to form a loop at top speed, but by means of a compounding control the looping effect can be adjusted to give the most desirable loop formation. The system, in allowing rapid changes in speed to be made and in providing a more suitable characteristic during impact drop, also provides a means for maintaining constant motor speed. However, the ultimate objective is not necessarily the maintenance of constant stand speed, but rather the maintenance of a constant loop. The slightest error in stand speed settings will cause the loop to change, and

Fig. 5.—One finishing stand, showing the hot strip passing over a looper

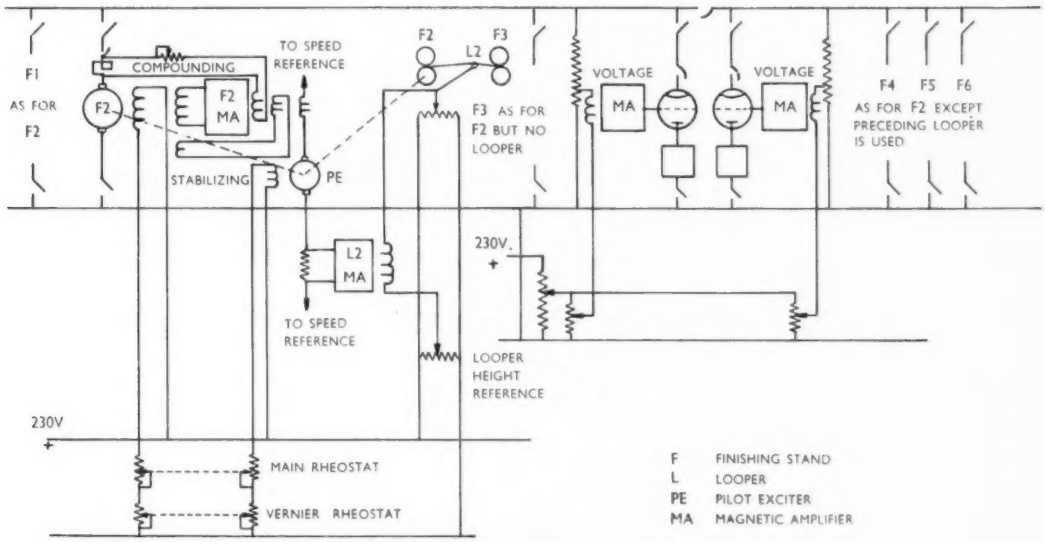


Fig. 6.—Speed and looper controls for finishing stands

for this reason an automatic looper control has been introduced at Brinsworth. This form of control was first used by The English Electric Company on a similar mill at Sandviken, Sweden, in 1952.

To support the loop of material between stands a looper arm and roller is used as shown in Fig. 5. The raising and lowering of this arm is initiated either by the operator or automatically from load relays in the motor armature circuits, which detect the presence of material in the stands. For fully automatic control of the finishing stand speeds, the position of the roller and hence the height of the loop above or below a desirable mean position is used to correct automatically the speed of its associated stand. Stand 3 is used as a reference stand, having no looper control, with stands 1 and 2 controlled by the loopers following them and stands 4, 5 and 6 by the loopers immediately preceding them.

Finishing Mill Control Scheme

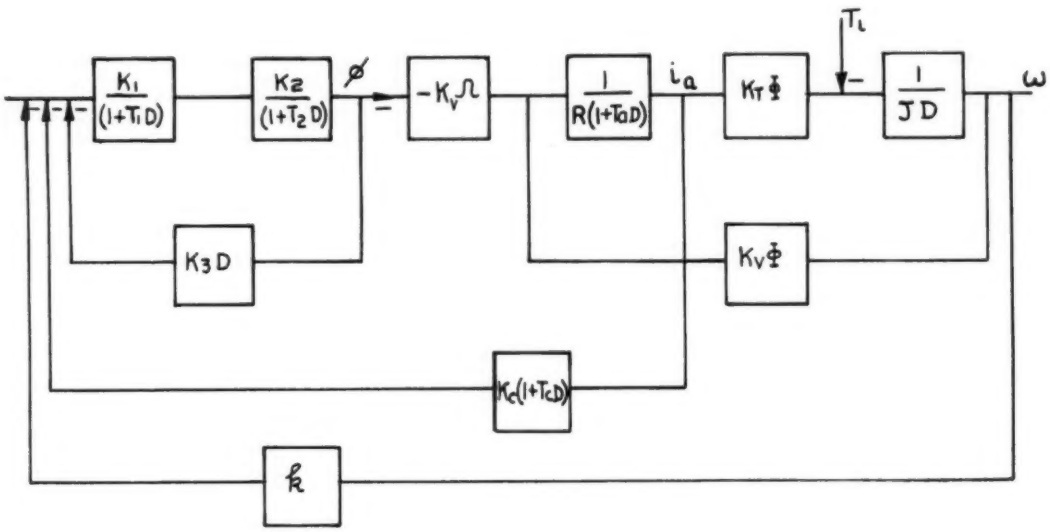
The complete control system for the finishing stands at Brinsworth is shown in simplified form in Fig. 6. The motor armatures may be supplied from either a common busbar or a split busbar. The latter allows the first three stands to be fed at a different voltage level to the last three stands, as a means for widening the available range of speed differentials of the stands. For either arrangement the armature voltage is maintained constant by two closed-loop rectifier voltage controls. Speed adjustment of each motor is obtained by a motorised field rheostat for large changes and a direct-operating vernier rheostat for smaller changes.

The closed loop speed control of each stand embraces a pilot exciter, the output voltage of which is a measure of the stand speed. This voltage is compared with a reference potential, the difference or error between these being fed to a magnetic amplifier in such a manner that the output of the magnetic amplifier, which supplies an auxiliary winding of the motor, will control the motor speed to reduce the error to a minimum.

The action of the closed loop speed control on each stand must be prevented from acting to maintain constant speed when either the armature voltage is varied or the motor speed is adjusted by varying the field rheostats. The first of these requirements is fulfilled by arranging that the speed reference potential varies linearly with the busbar voltage. The second requirement is met by arranging for the excitation of the pilot exciter to vary with the main motor field excitation, in

such a manner that throughout the speed range of the motor the pilot exciter voltage remains constant.

Any tendency for the motor speed to change due to a random change in temperature will be corrected by the speed control, but there is no such automatic corrective action for temperature changes on the pilot exciter field. For this reason a swamping resistance is used in series with this field so that temperature has a negligible effect upon its excitation. Not only does this counteract one of the main sources of speed variation in the system, but it imparts to the pilot exciter a very small field time-constant. When changing a stand speed by varying both the motor field rheostat and the pilot exciter field rheostat, it is the latter which has the more rapid effect upon the system. The change in pilot exciter voltage acts as a disturbance to the speed control, causing the closed loop control



$\frac{K_1}{(1+T_1D)}$	MAGNETIC AMPLIFIER TRANSFER FUNCTION	f_R	PILOT EXCITER CONSTANT
$\frac{K_2}{(1+T_2D)}$	MOTOR FIELD TRANSFER FUNCTION	J	INERTIA OF MOTOR AND LOAD
$K_V\ K_T$	MOTOR CONSTANTS	i_a	MOTOR ARMATURE CURRENT
Φ	MOTOR FLUX	K_3	STABILIZING CONSTANT
ϕ	CHANGES IN FLUX	ω	MOTOR SPEED
R	MOTOR ARMATURE CIRCUIT RESISTANCE	ω	CHANGES IN MOTOR SPEED
$K_C(1+T_CD)$	COMPOUNDING TRANSFER FUNCTION	T_L	LOAD TORQUE

Fig. 7.—Block diagram representing the speed controls on the finishing stands

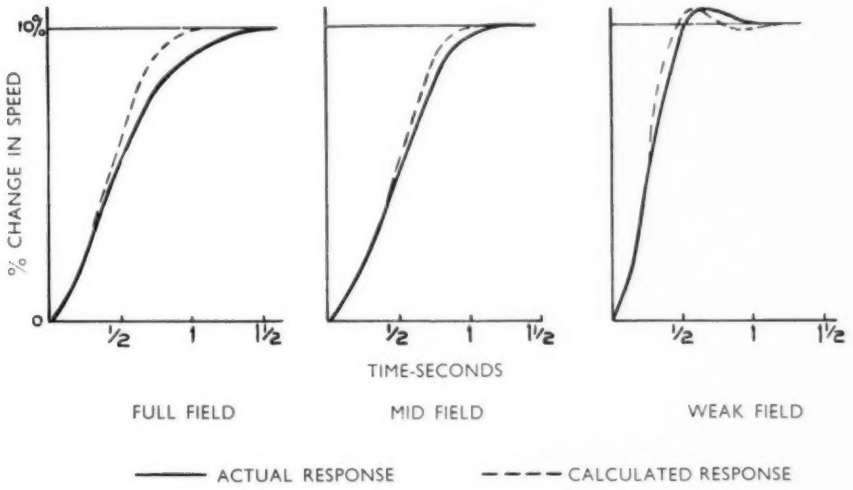


Fig. 8.—Comparison of actual and calculated responses

through the auxiliary field to force the motor excitation to give the new desired speed. The slower change in the main motor field then takes over from the auxiliary field, in its own time, without disturbing the new speed setting of the motor.

The automatic looper control utilizes a potentiometer with a moving slider attached to the looper arm. The potential at this slider is compared with that of a reference potentiometer, and the difference used to control an auxiliary magnetic amplifier. The output of this magnetic amplifier is fed in series with the speed control reference of its associated stand speed control and also to the motor of the motorised field rheostat of that stand drive. An out-of-balance of the potentials in the potentiometer bridge, caused by a change in the looper

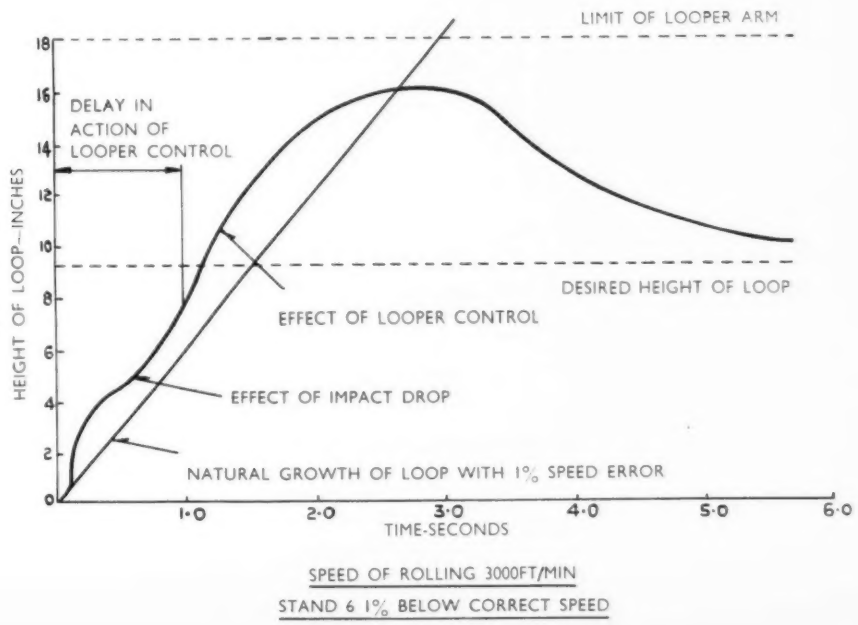


Fig. 9.—Characteristic of looper control when correcting for an error in speed setting

arm position, will cause the output from the auxiliary magnetic amplifier to buck or boost the speed reference of the stand speed control, and so correct for the change in position of the looper arm. The range of the speed control is limited by the capabilities of the auxiliary control winding on the motor. Although in acting upon the speed control a fast correction is obtained for movements of the looper arm, the use of the speed control to correct permanently for errors in speed setting must be prevented. The action of the looper magnetic amplifier on the field rheostat motor is used for this purpose, causing the main rheostat to move and correct for large errors in speed setting.

Design of the Speed Control

The main problem in the design of a speed control utilizing a motor field is in the analysis of the stability of the system, which represents a non-linear problem. The non-linear effect makes itself felt as a continuous change in certain circuit parameters as the field excitation changes. The analysis for the Brinsworth drives was based upon the fact that at any given speed setting the control system would be called upon to make only small variations in the motor excitation, either to correct for impact speed drop effects or to effect a vernier change in motor speed. Analysis was therefore carried out at various speed settings, assuming a linear relationship to exist at each speed setting. The block diagram representing the linearised system used for analysis is shown in Fig. 7. An overall appreciation of the calculations, carried out under several running conditions, indicated that a stabilising winding on the motor field would give rise to a stabilising signal to satisfy all conditions. The validity of this approach is indicated in Fig. 8, which shows the calculated responses to changes in speed at three settings compared with those obtained in practice.

Based upon these results, Fig. 9 shows the action of the looper control in correcting for an error in speed setting on the last stand. A significant factor affecting the characteristic is the necessity of delaying the action of the looper control in order to afford time for the arm to rise and for the roller to contact the strip. The example shown in Fig. 9 represents a rather extreme condition of incorrect operation. In practice, initial mill speed adjustment is carried out to within closer limits on manual control, and the looper control then switched in to maintain the correct rolling conditions. In this capacity the looper control has remained in operation throughout long rolling schedules, providing a valuable aid to the operators.

Conclusion

In conclusion it is apparent that at the Brinsworth Mill, closed loop controls have been used not only as necessary additions for higher production rates but also as worth-while means for improving electrical efficiency and for relieving operator fatigue.

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